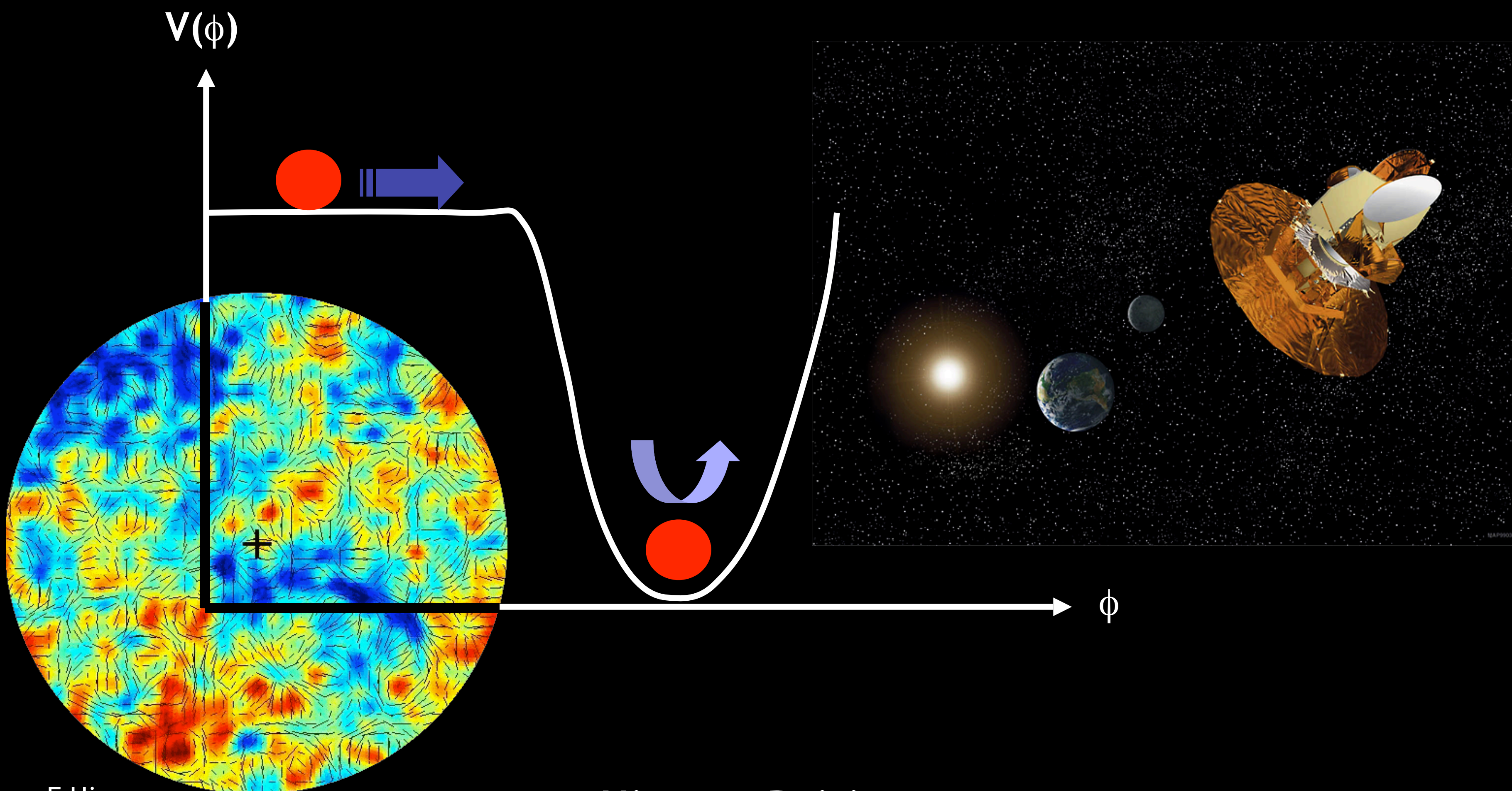
Understanding Cosmic Acceleration



E Hivon

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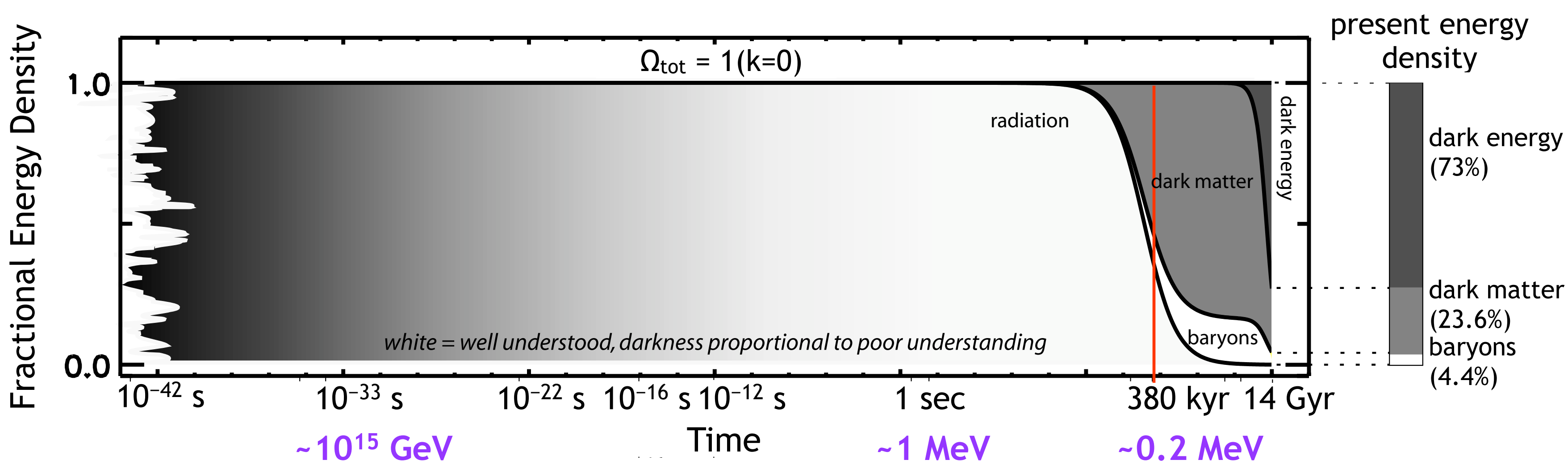
Cosmic History / Cosmic Mystery



~10^{15} GeV ~1 MeV ~0.2 MeV

Planck Energy

GUT symmetry

T=100 TeV (ILC X 100)

nucleosynthesis

Generation of primordial perturbations

Cosmic Microwave Background Emitted carries signature of acoustic oscillations and potentially primordial gravitational waves

non-linear growth of perturbations: signature on CMB through weak gravitational lensing

Diagram adapted from Jeff McMahon's Thesis

Roadmap

- Background: cosmic acceleration
  - Inflation
  - Dark energy
- Constraining Inflation with Cosmological Data
  - “Worked example”: Cosmic Microwave Background
  - WMAP data and “standard” inflationary constraints
  - Slow Roll Reconstruction: connecting theory and data
  - Future Prospects
- Constraining Dark Energy with Cosmological Data
  - Extending reconstruction toolbox to dark energy
  - Dynamics of generic quintessence potentials
  - Future Prospects

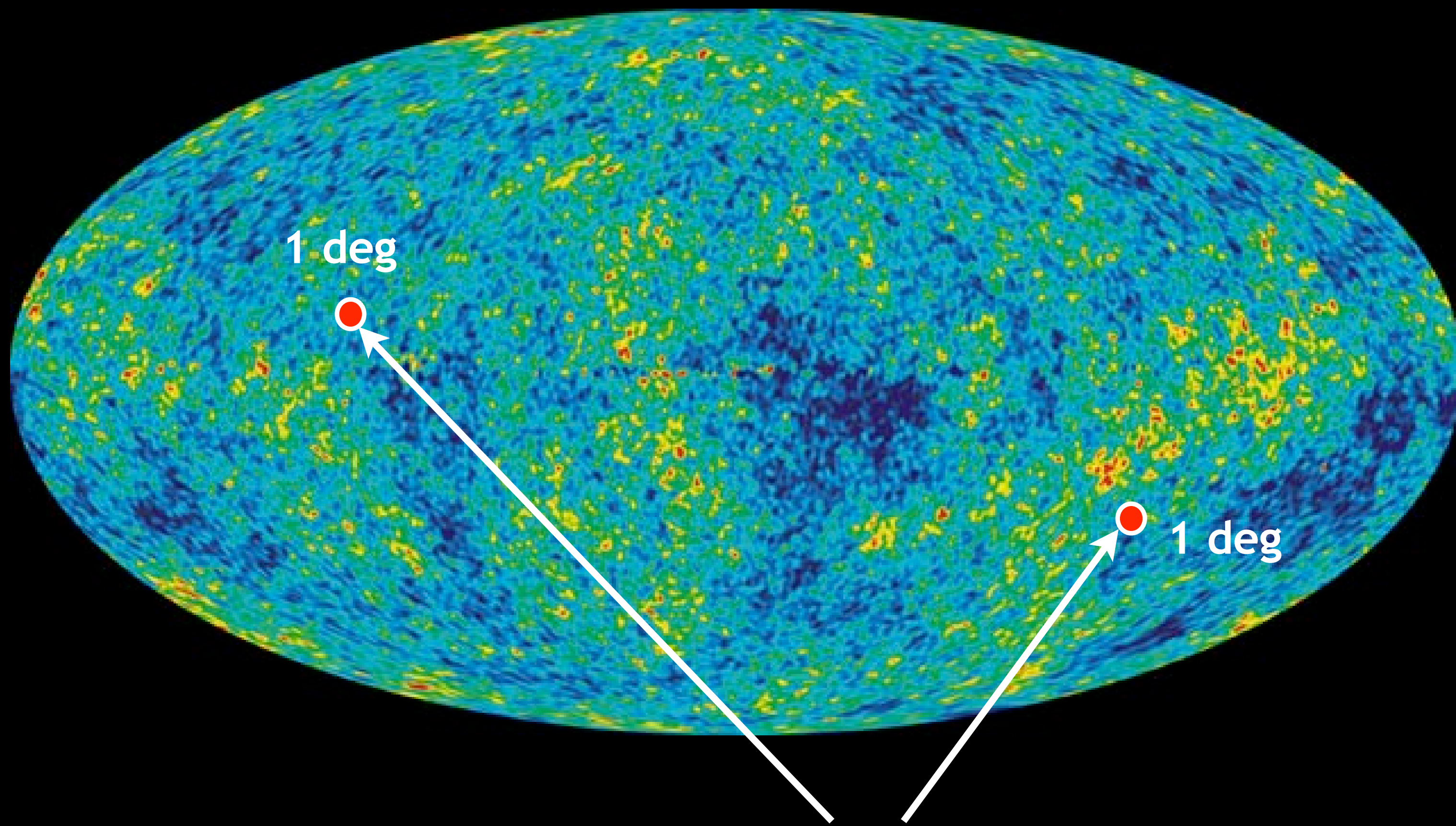
The Cosmic Microwave Background (CMB)

Credit: NASA/WMAP Science Team

The Horizon Problem

In Standard Big Bang Model, horizon scale at CMB release subtends ~ 1 deg

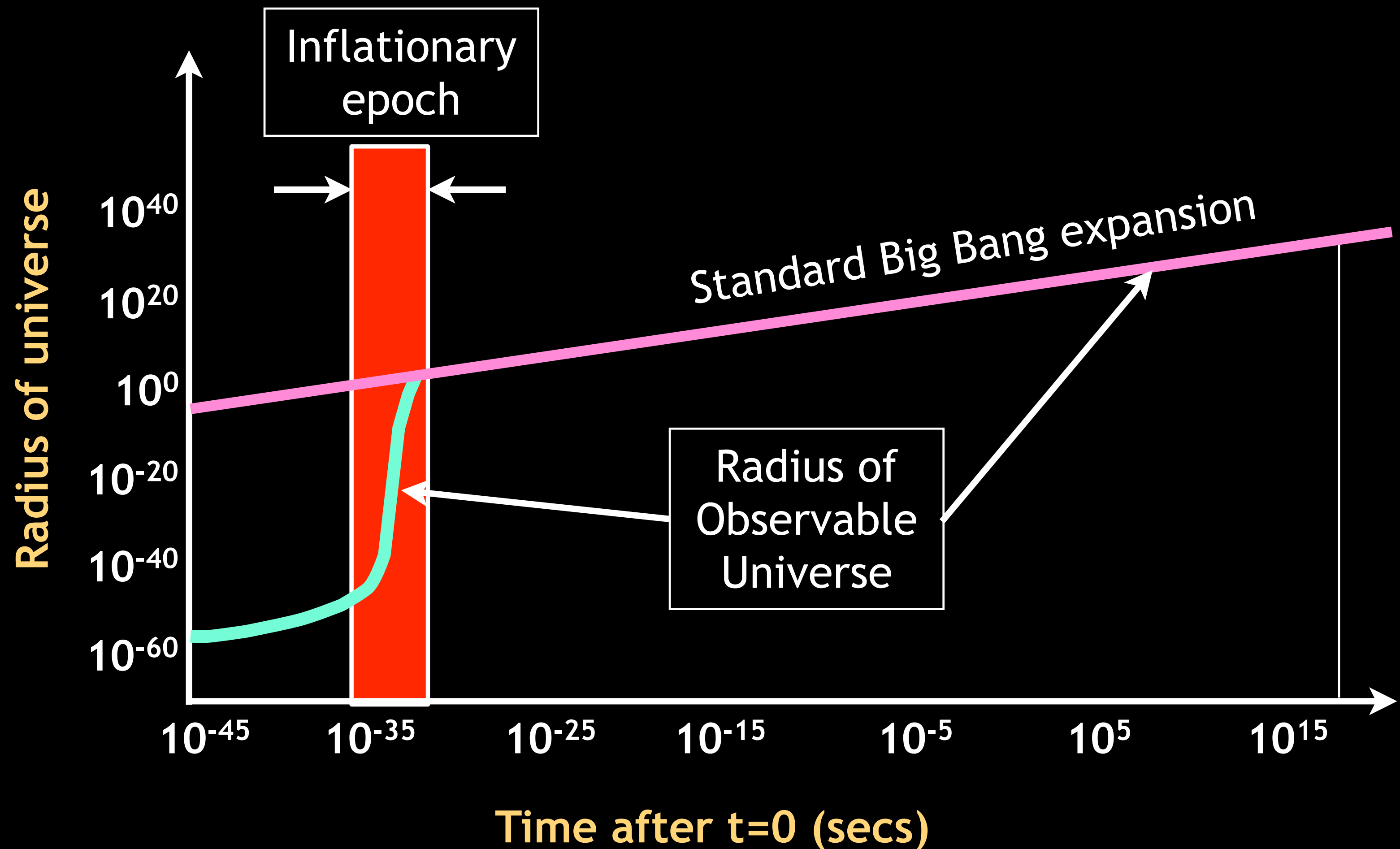
Regions separated by more than 1 deg could not have interacted previously



So why is the temperature of these patches the same to 1/100000?

Credit: NASA/WMAP Science Team

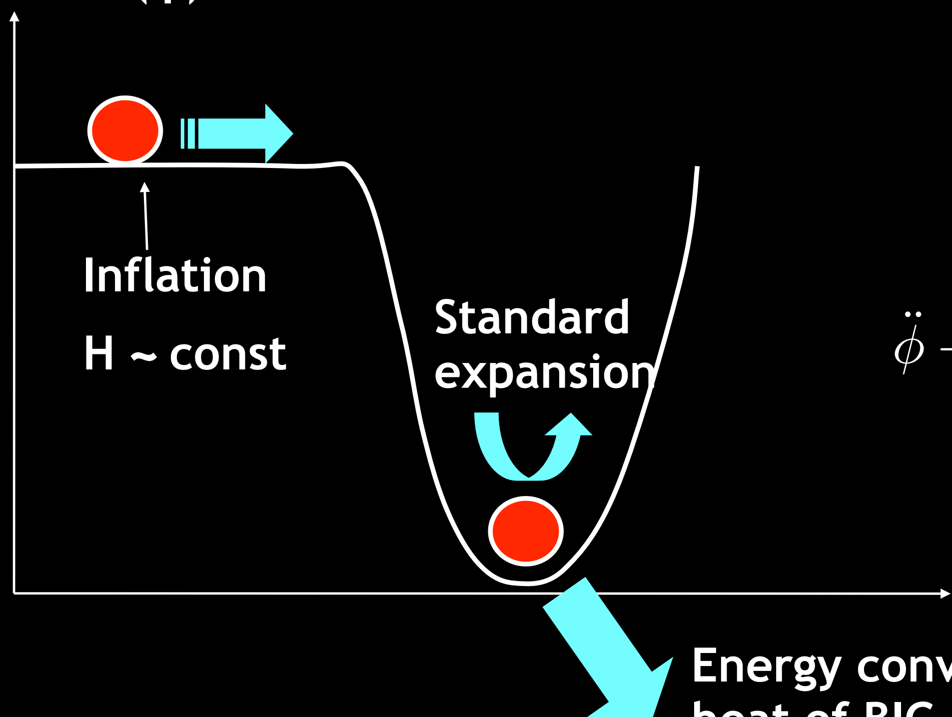
Inflation: vacuum-driven super-expansion



If inflation lasts long enough, CMB patches on opposite sides of the sky would have been close enough to communicate in the primordial times.

Inflation

Implemented as a slowly-rolling scalar field evolving in a potential:



$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\left[\frac{1}{2}\dot{\phi}^2 + V(\phi)\right]$$

expansion rate

density

$$\ddot{\phi} + 3H\dot{\phi} + V' = 0$$

friction

Guth (1981), Linde (1982), Albrecht & Steinhardt (1982), Sato (1981), Mukhanov & Chibisov (1981), Hawking (1982), Guth & Pi (1982), Starobinsky (1982), J. Bardeen, P.J. Steinhardt, M. Turner (1983), Mukhanov et al. 1992), Parker (1969), Birrell and Davies (1982)

Perturbations from inflation

Cosmological perturbations arise from quantum fluctuations, evolve classically.

$$P_\phi(k) \simeq \hbar \left(\frac{H}{2\pi}\right)^2$$

$$P_{\mathcal{R}} \simeq \frac{\hbar}{4\pi^2}\left(\frac{H^4}{\dot{\phi}^2}\right)^2_{k=aH}$$ scalar

$$P_h \simeq \frac{2\hbar}{\pi^2}\left(\frac{H}{m_{\rm Pl}}\right)^2_{k=aH}$$ tensor

The dark side of the universe

density

pressure

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3P)$$

$$w = \frac{P}{\rho} < -\frac{1}{3} \quad \text{for acceleration}$$

Independent lines of evidence for dark energy:

- Type Ia supernovae (standard candles): the universe is accelerating in its expansion
- CMB (standard ruler): the universe is at the critical density (i.e. its geometry is flat)
- Galaxy surveys: 27% of the density of the universe behaves as (atomic +dark) matter

Riess et al. (1998), Perlmutter et al. (1999), Spergel et al. (2003), Peacock et al. (2001), Tegmark et al. (2003)

What is the nature of dark energy?

Possibilities:

- Λ: vacuum energy, a.k.a. cosmological constant
- Q : scalar field (slowly varying dynamical component)
- A modification to General Relativity

$$G_{\mu\nu} \equiv \mathcal{R}_{\mu\nu} - \frac{1}{2} g_{\mu\nu} \mathcal{R} = 8\pi G T_{\mu\nu} + \Lambda g_{\mu\nu}$$

Peebles and Ratra (1987), Frieman and Olinto (1990), Caldwell, Dave & Steinhardt (1998)

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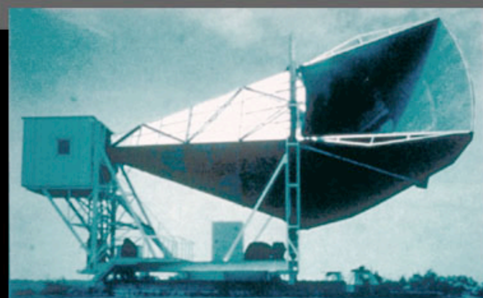
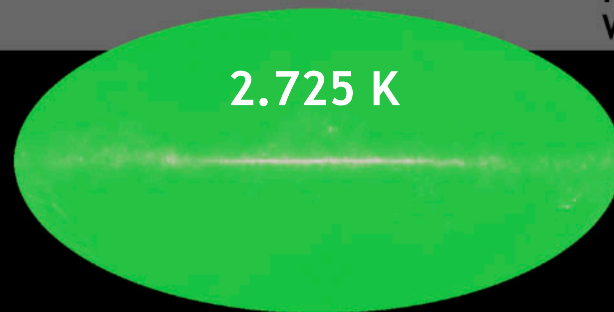
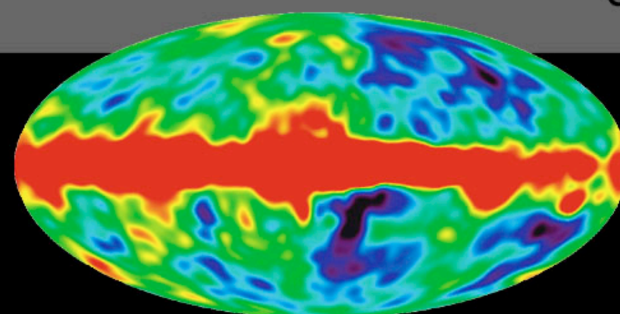
History of CMB temperature measurements

1965 Penzias and Wilson

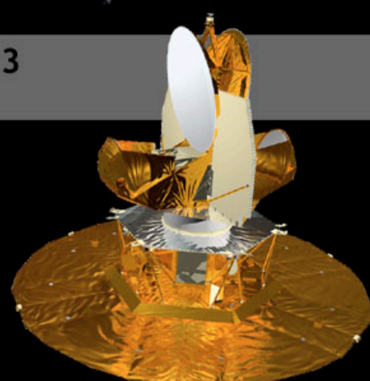


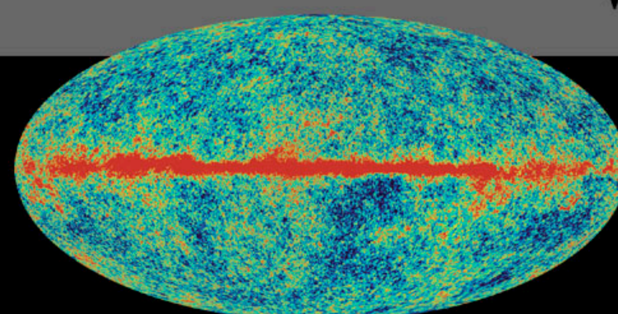


1992 COBE



2003 WMAP





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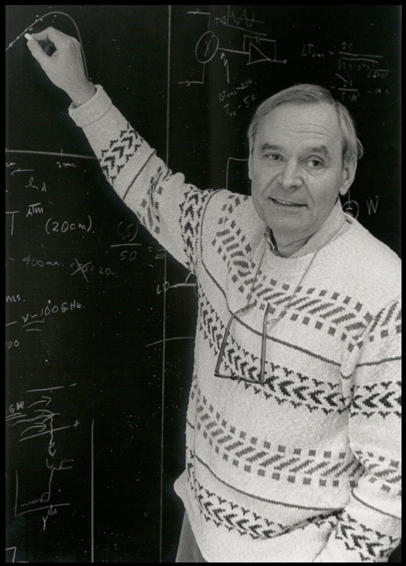

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Compress the CMB map to study cosmology

Express sky as: $$\delta T(\theta,\phi) = \sum_{l,m} a_{lm} Y_{lm}(\theta,\phi)$$

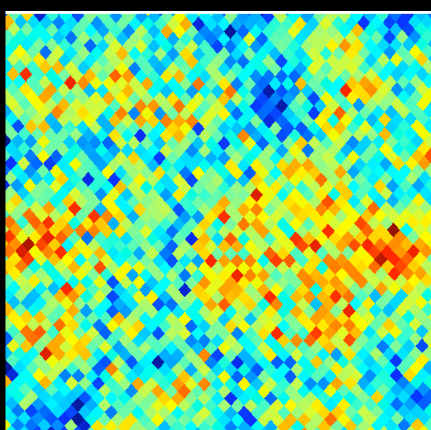
If the anisotropy is a Gaussian random field

(real and imaginary parts of each a_{lm} independent normal deviates, not correlated)

all the statistical information is contained in the angular power spectrum.

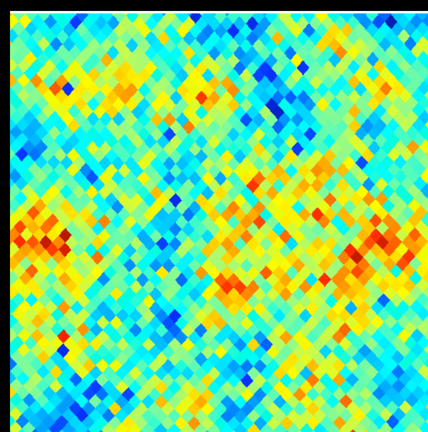
Komatsu et al. (2003)

0.06% of map



X

5 deg



1 deg

Raw 94 GHz
near NEP

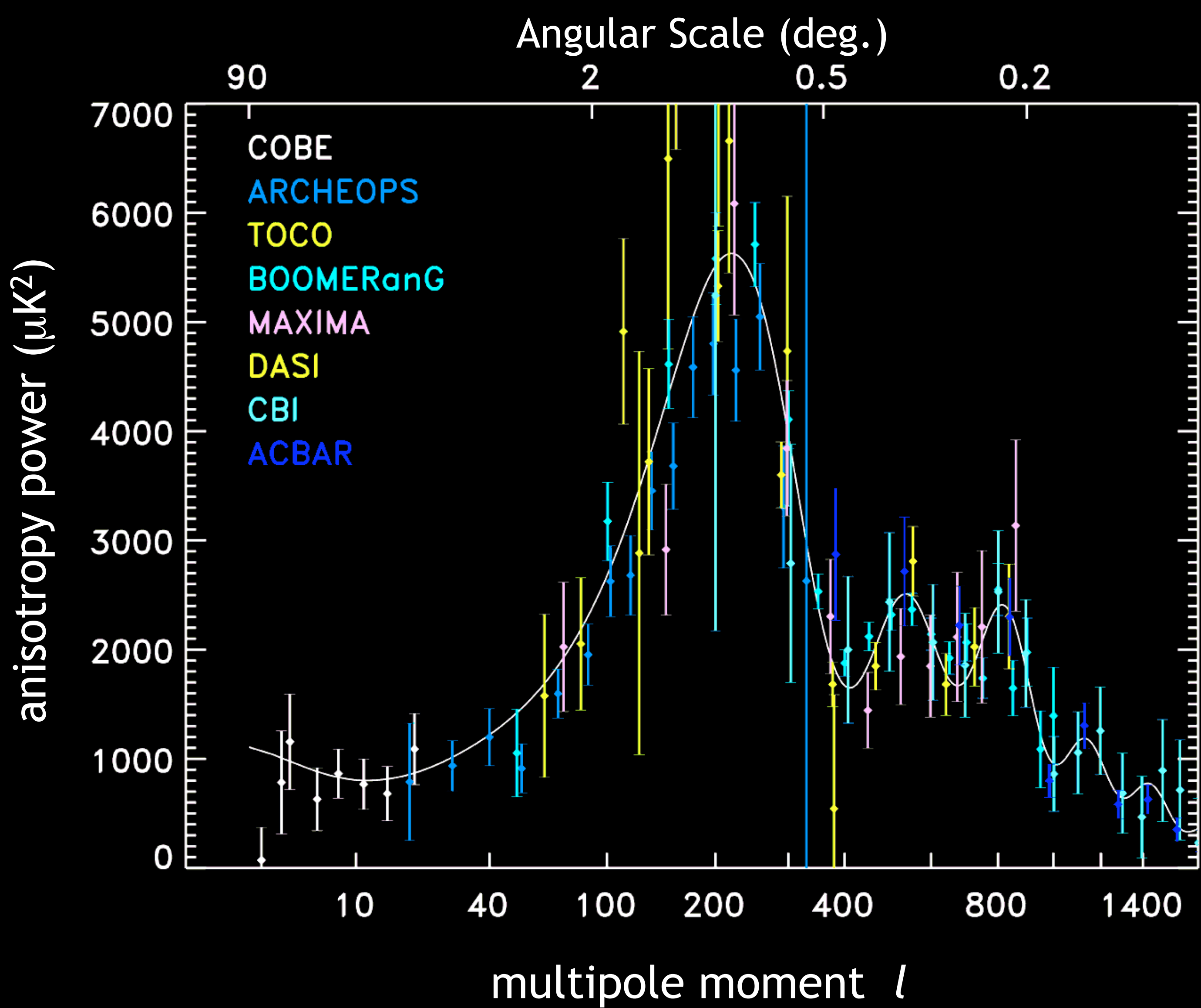
+/- 32 uK

Raw 61 GHz
near NEP

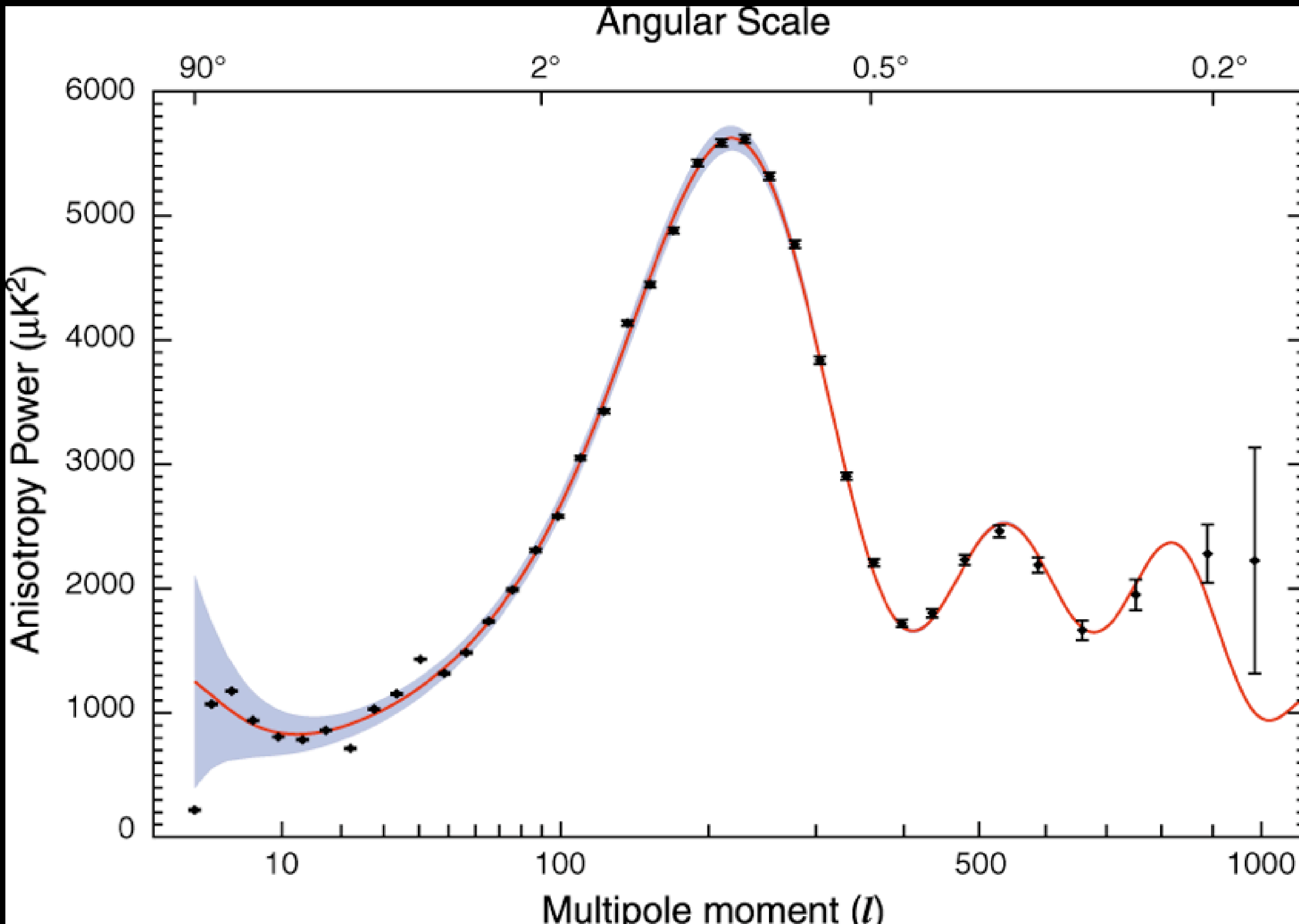
$$C_l = \frac{1}{2\ell+1}\sum_m |a_{lm}|^2$$

ANGULAR POWER SPECTRUM

Power Spectrum Measurements Before WMAP



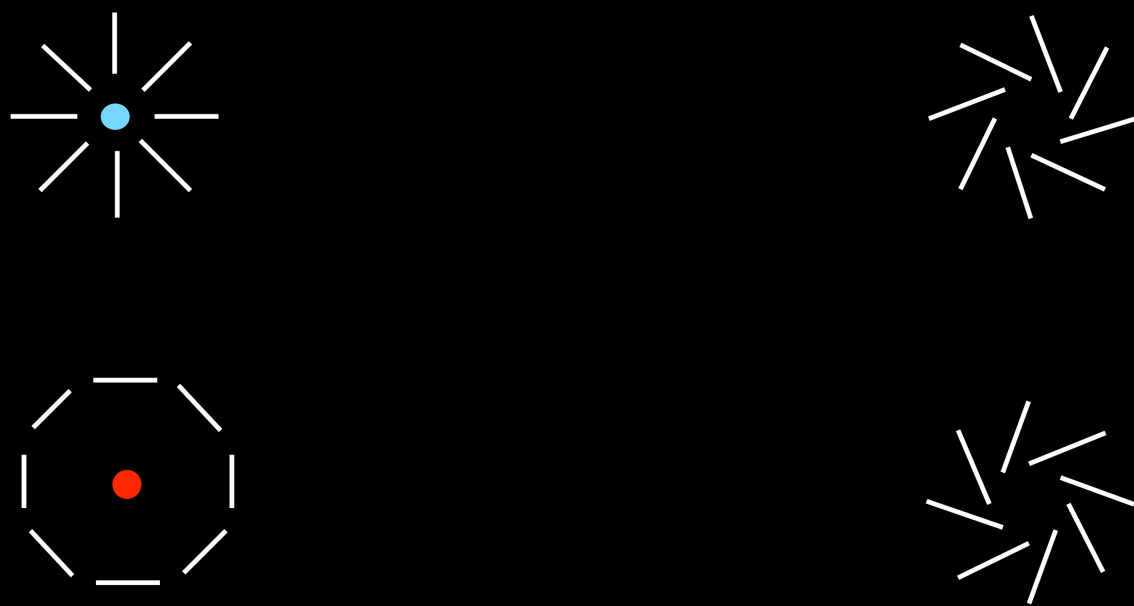
WMAP 3 year temperature power spectrum



Hinshaw et al. (2003)

Types of CMB polarization

CMB polarization can be decomposed into two orthogonal modes. E-mode is the curl-free mode ("Electric"). B-mode is the divergence-free mode ("Magnetic").

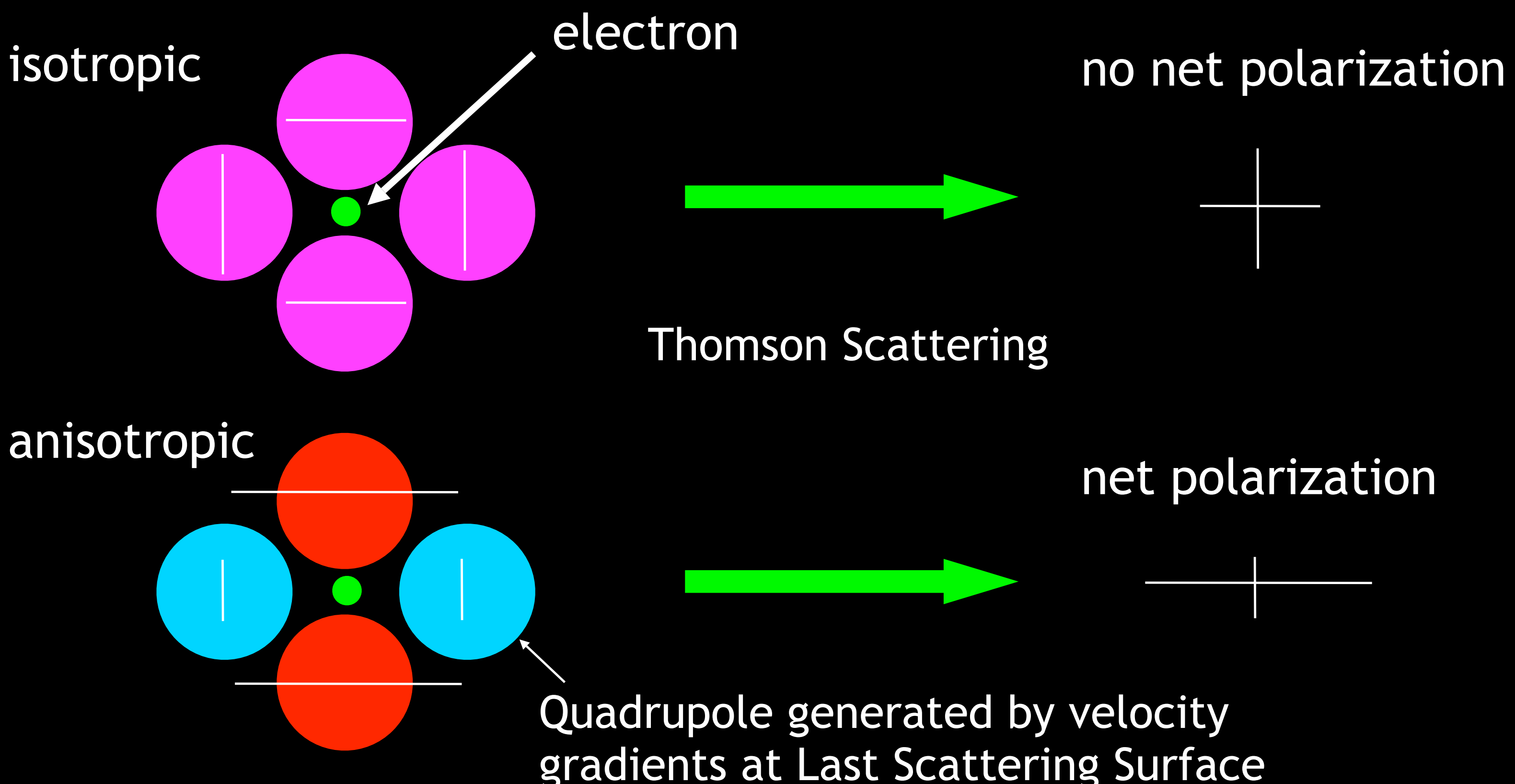


E-mode B-mode

B mode discriminates between scalar and tensor perturbations

Generation of CMB polarization

- Temperature quadrupole at the surface of last scatter generates polarization.



Polarization by metric tensor perturbations

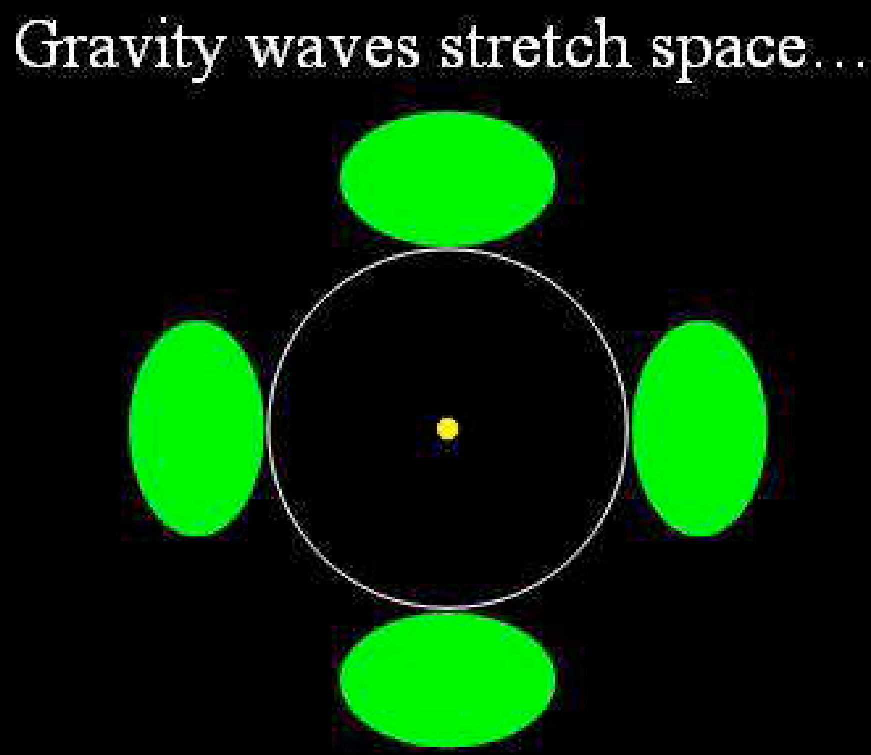


Image from J. Ruhl

… and create variations

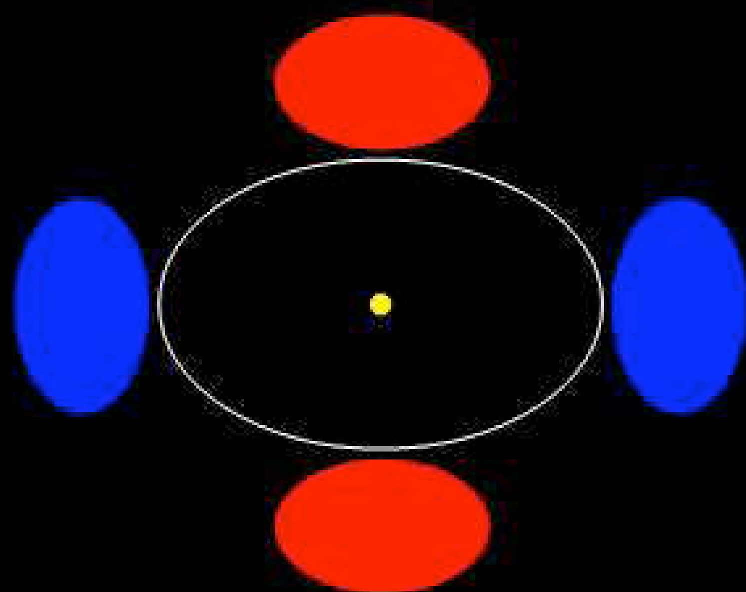


Image from J. Ruhl

Generation of CMB Polarization

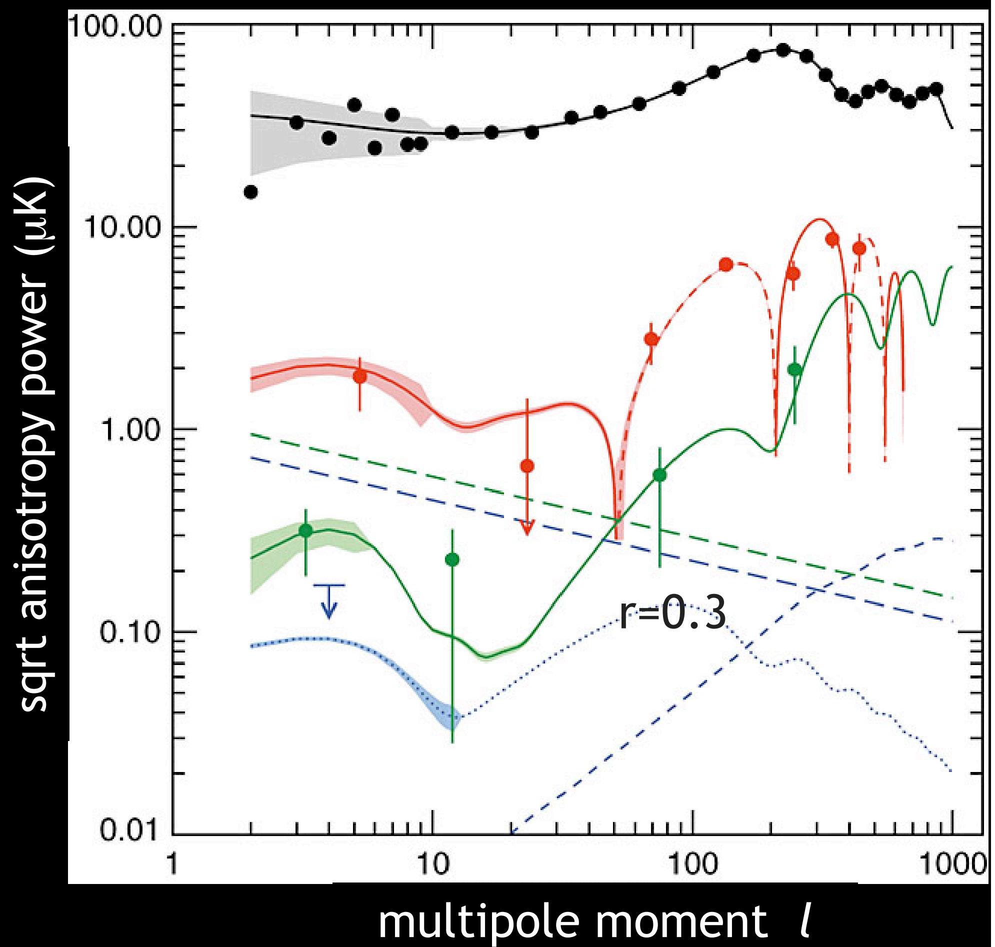
1. z=1089 decoupling:
   scattering of CMB from electrons with non-random velocities
   polarization correlates with temperature map
   1st detected by DASI, now have power spectrum

2. z~10 reionization:
   scattering of CMB from free electrons
   uniformly suppress l>40 anisotropy by 30% (!)
   First detected by WMAPI in temp-pol cross correlation
   Now have polarization auto-power spectrum.

3. Gravitational waves:
   Inflation-generated gravity waves polarize CMB
   not observed yet!

WMAP 3 year polarization data

- Three Years (TE,EE,BB)
  - Foreground Removal
    - Done in pixel space
  - Null Tests
    - Year Difference & TB, EB, BB
  - Data Combination
    - Only Q and V are used
  - Data Weighting
    - Optimal weighting (C^{-1})
  - Likelihood Form
    - Gaussian for the pixel data
    - C_l not used at $l<23$



temperature
temp X E-pol
E-pol
B-pol (68% upper limit)

Page et al. (2006)

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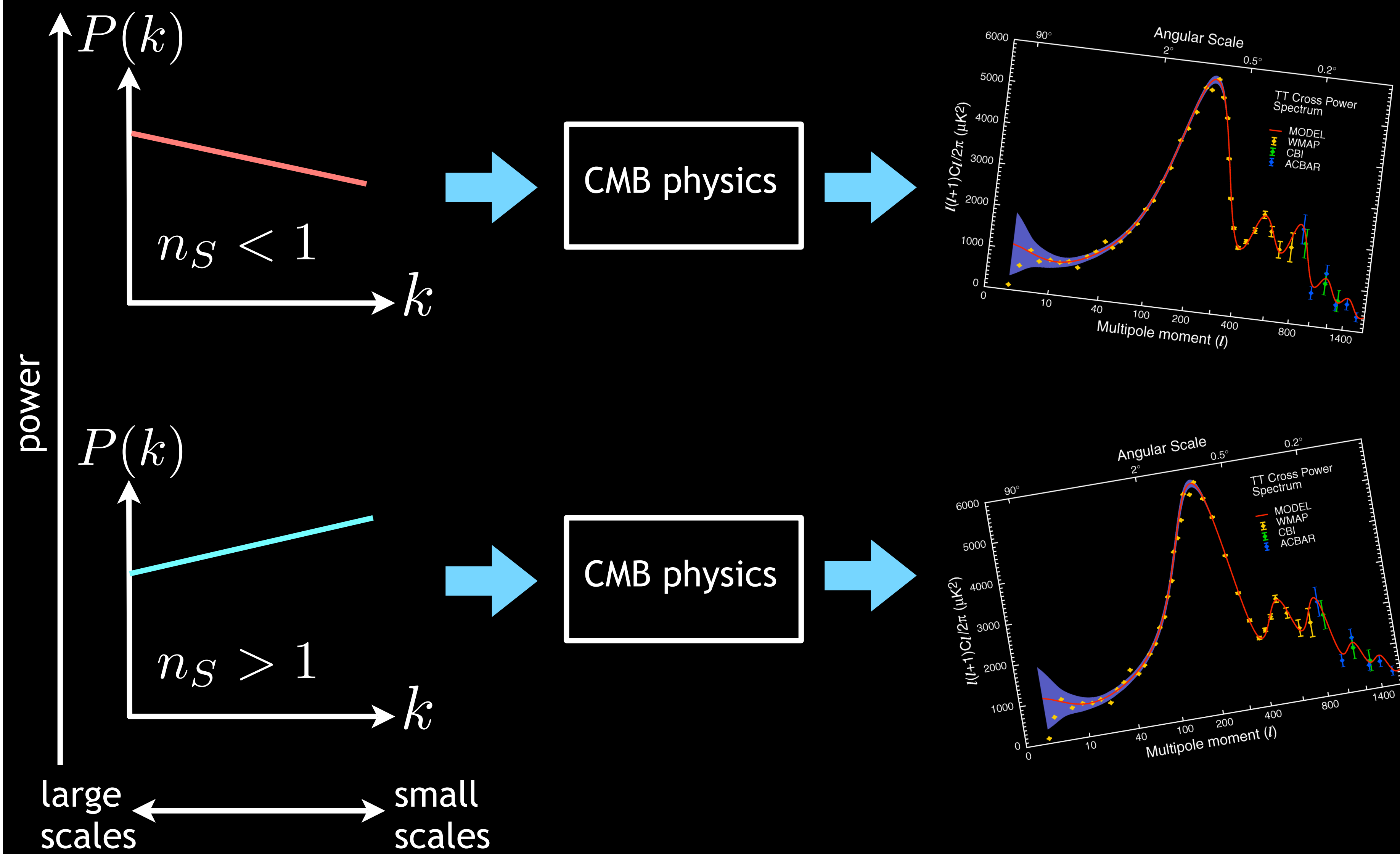
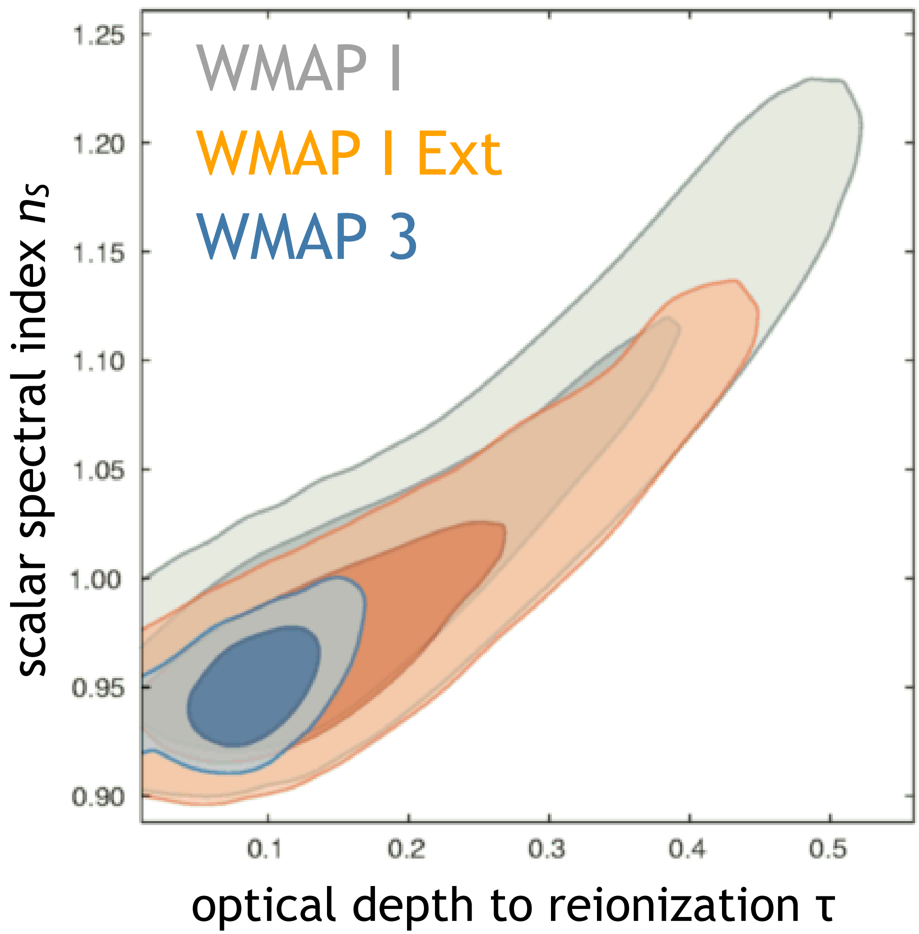
Constraining the Primordial Power Spectrum



What does inflation have to do with the first stars?



Reducing the noise by sqrt(time) → degeneracies broken

Spergel et al (WMAP Collaboration) (astro-ph/0603449)

Generic predictions of simplest inflation models

- Nearly scale invariant primordial fluctuations [COBE]:
  - WMAP3: $n_s = 0.960 \pm 0.016$ $\qquad P(k) \propto k^{n_s-1}$
- Flatness of the universe [TOCO, BOOMERanG, Maxima, Archeops, ..., WMAPI]
  - WMAP3 + HST prior:
  - $\Omega_k = -0.014 \pm 0.017$

$$\Omega_k = -\frac{\kappa}{a^2 H^2}$$

- Gaussianity of primordial perturbations [WMAPI]
  - WMAP3: $-54 < f_{NL} < 114$ (95%)

$$\begin{aligned} \Phi(\vec{x}) &= \Phi_{\rm G}(\vec{x}) \\ &+ f_{NL}\left[\Phi^2_{\rm G}(\vec{x})\right] \end{aligned}$$

- Adiabatic initial conditions and superhorizon fluctuations [large scale TE anticorrelation, WMAPI]

Spergel, Verde, Peiris et al. (2003), Komatsu et al. (2003), Peiris et al. (2003), Spergel et al (WMAP Collaboration) (astro-ph/0603449)

Detailed Predictions of Inflation Models

- The primordial power spectrum is not a perfect power law.

$$n_s(k) = n_s(k_0) + \alpha \ln\left(\frac{k}{k_0}\right)$$

"running": $dn_s/d\ln k$

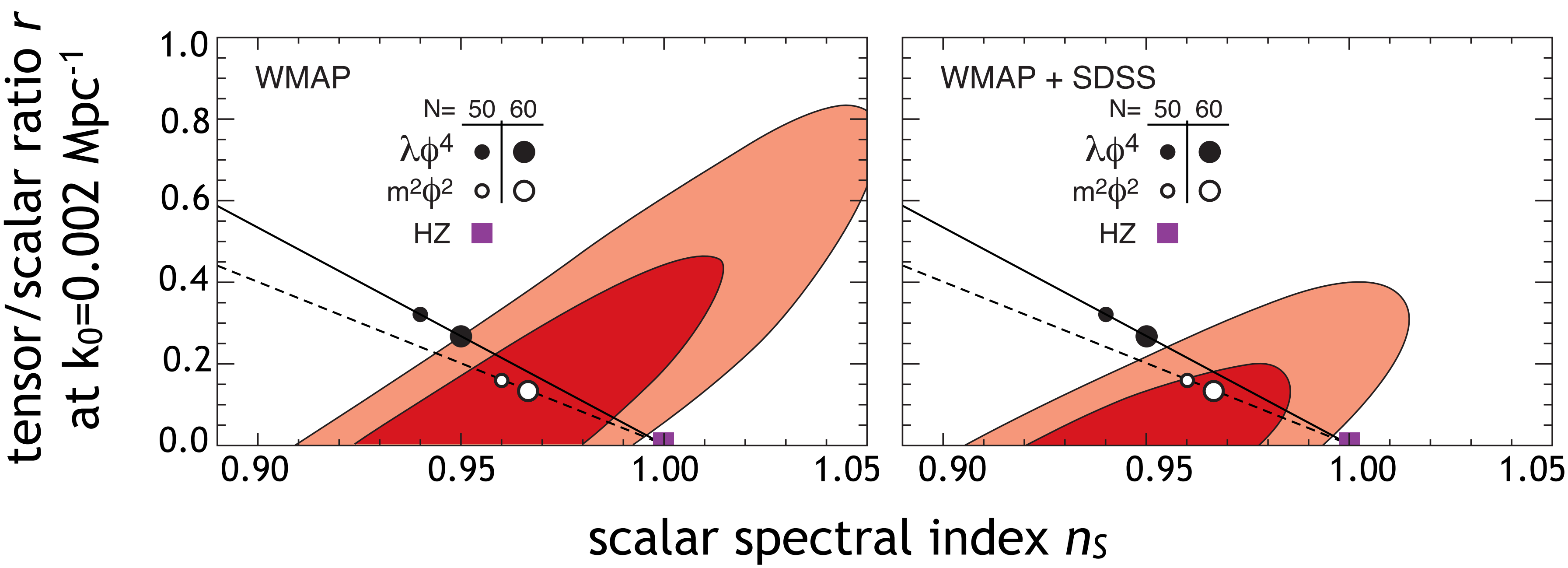
- There could be observable gravitational waves.

$$r \equiv \text{tensor-to-scalar ratio} = \frac{\langle h_{ij}h^{ij}\rangle(k_0)}{\langle \mathscr{R}\mathscr{R}\rangle(k_0)}$$

(The shape of the tensor power spectrum is determined by $n_t = -r/8$ using predictions of single field inflationary models.)

We use $k_0 = 0.002\ \mathrm{Mpc}^{-1}$ ($l \sim 30$)

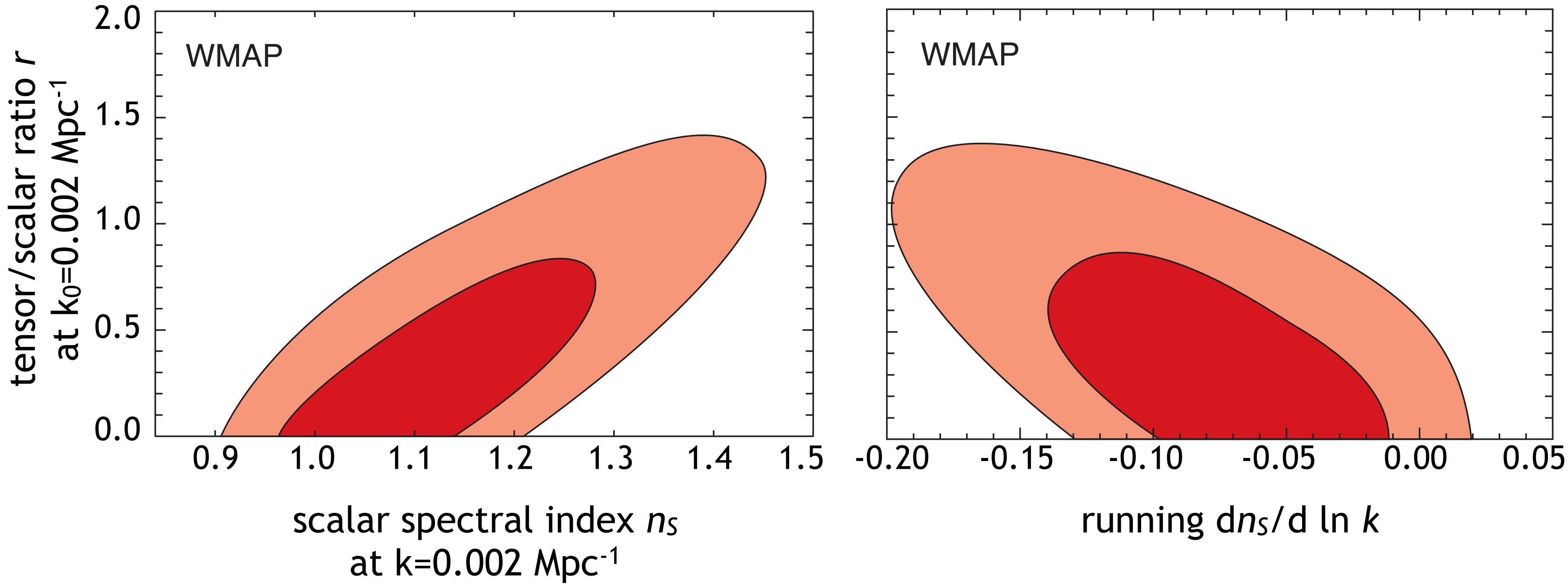
Constraints on tensor modes



- Both the scale-invariant Harrison-Zel'dovich power spectrum and the $\lambda\ \phi^4$ model are disfavoured w.r.t. to the $m^2\ \phi^2$ model by likelihood ratios greater than 50.

Spergel et al (WMAP Collaboration) (astro-ph/0603449)

Constraints on tensor modes and a running index



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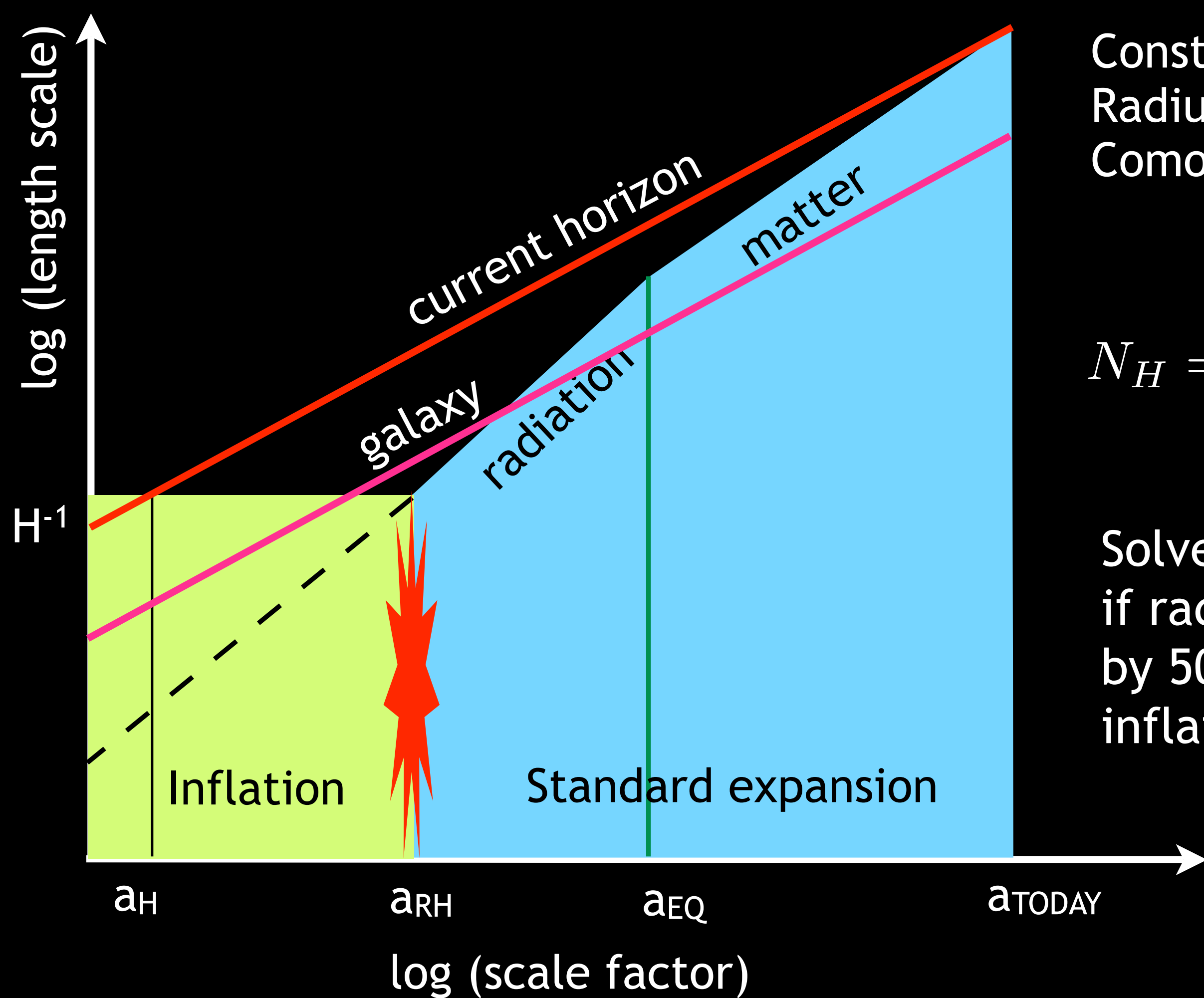
The duration of inflation

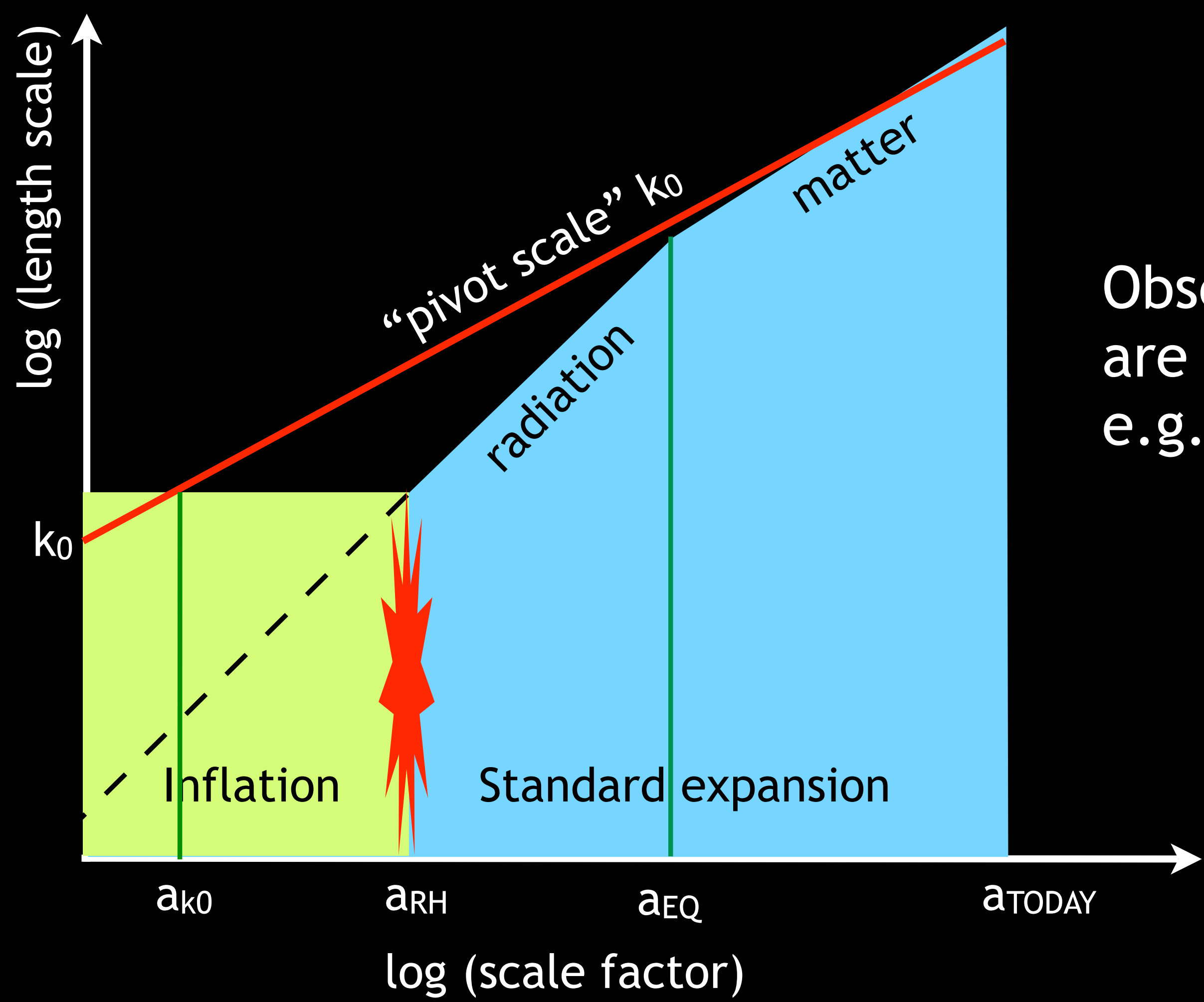


Constraint: Comoving Hubble Radius at onset of inflation > Comoving Hubble Radius today.

$$N_H = \ln\left(\frac{a_{RH}}{a_H}\right) \simeq 50 - 60$$

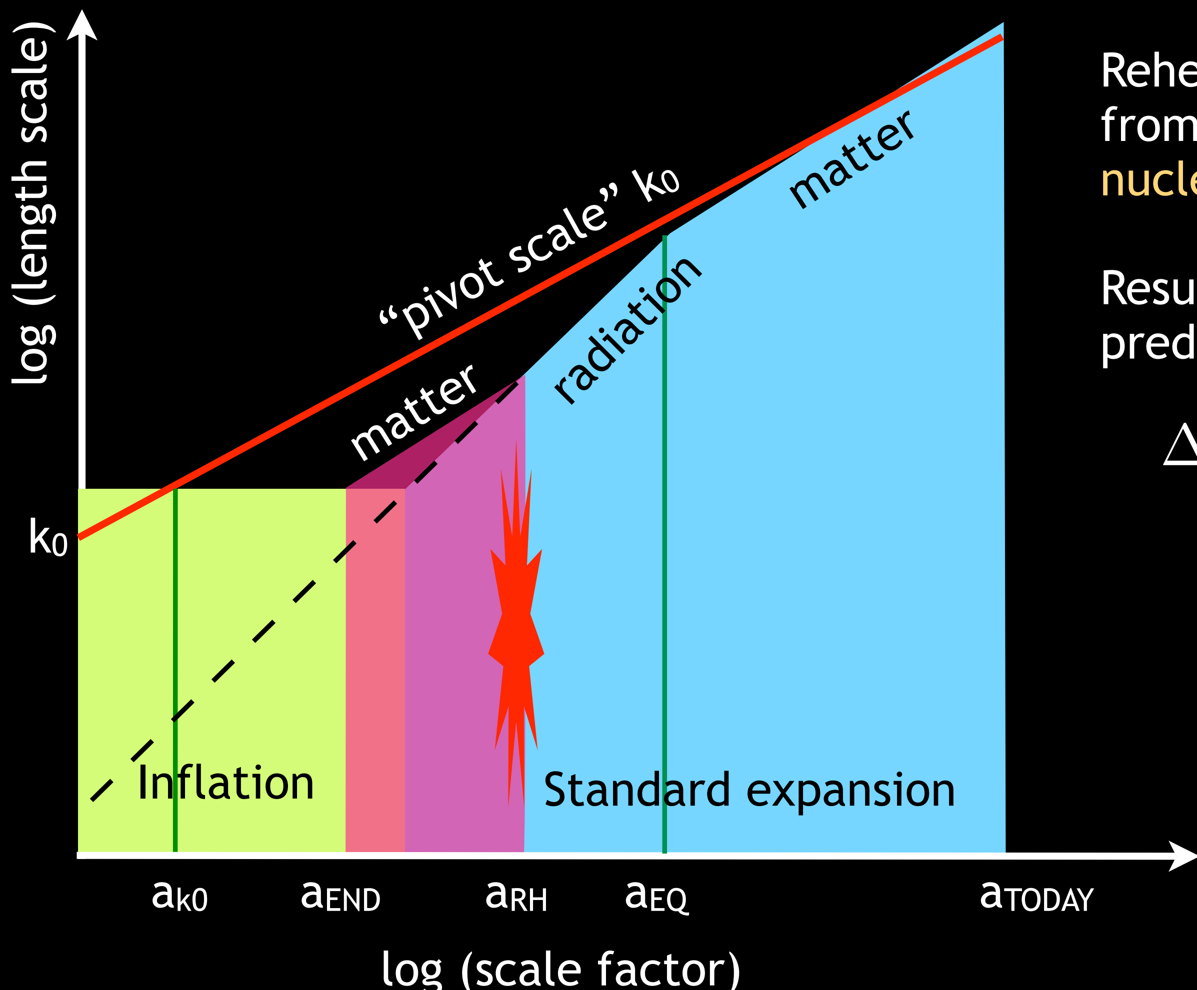
Solves cosmological problems if radius of universe expands by 50-60 “e-folds” during inflation

Connecting measurements to an inflationary model



Observable parameters are a function of scale! e.g. $n_S[k(N_{efold})]$

Connecting measurements to an inflationary model



Reheat temperature can vary from GUT scale (10^{15} GeV) to nucleosynthesis scale (1 MeV)!

Resulting uncertainty in predictions at a given "pivot":

$$\Delta N_{\rm efold} \sim 14$$

$$\frac{\Delta r}{r} \sim 1$$

$$\Delta n \sim 0.02$$

Spectral index vs. Slow roll reconstruction

- Spectrum characterized by index and amplitude
  - These are empirical quantities
  - No fundamental significance
  - Implicitly assume smoothness
  - No immediate correlation between observable scale and potential

- We fit to the derivatives of the expansion rate
  - From these we can rebuild the potential
  - “Thorough” inflationary prior.
  - Do not explicitly drop smoothness

$$\epsilon \propto \left(\frac{H'}{H}\right)^2 \qquad \eta \propto \frac{H''}{H} \qquad \xi \propto \frac{H'''H'}{H^2} \qquad \text{etc.}$$

SLOPE CURVATURE JERK

Peiris & Easther (astro-ph/0603587), Peiris & Easther (astro-ph/0609003)

Inflationary Observables

$$P_{\mathcal{R}} = \frac{[1-(2C+1)\epsilon + C\eta]^2}{\pi\epsilon}\left(\frac{H}{m_{\rm Pl}}\right)^2\Bigg|_{k=aH},$$

$$P_h = [1-(C+1)\epsilon]^2\,\frac{16}{\pi}\left(\frac{H}{m_{\rm Pl}}\right)^2\Bigg|_{k=aH},$$

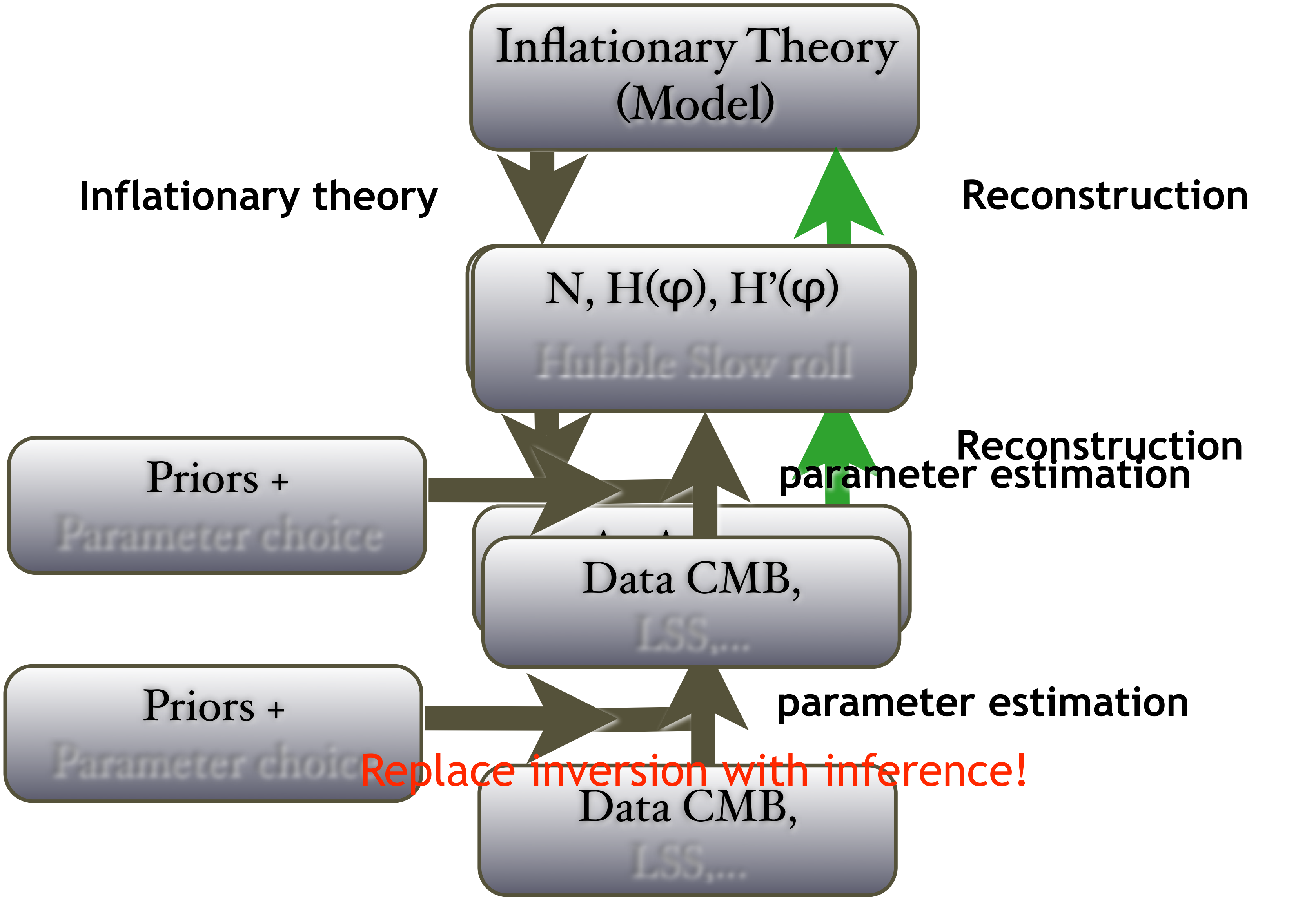
$$C = -2+\ln 2+\gamma \approx -0.729637$$

Lidsey et al (1995)

- Avoids the use of a pivot scale
- Could compute the spectrum exactly if needed
- Can include constraints on duration of inflation and reheating

Peiris & Easther (astro-ph/0603587), Peiris & Easther (astro-ph/0609003)

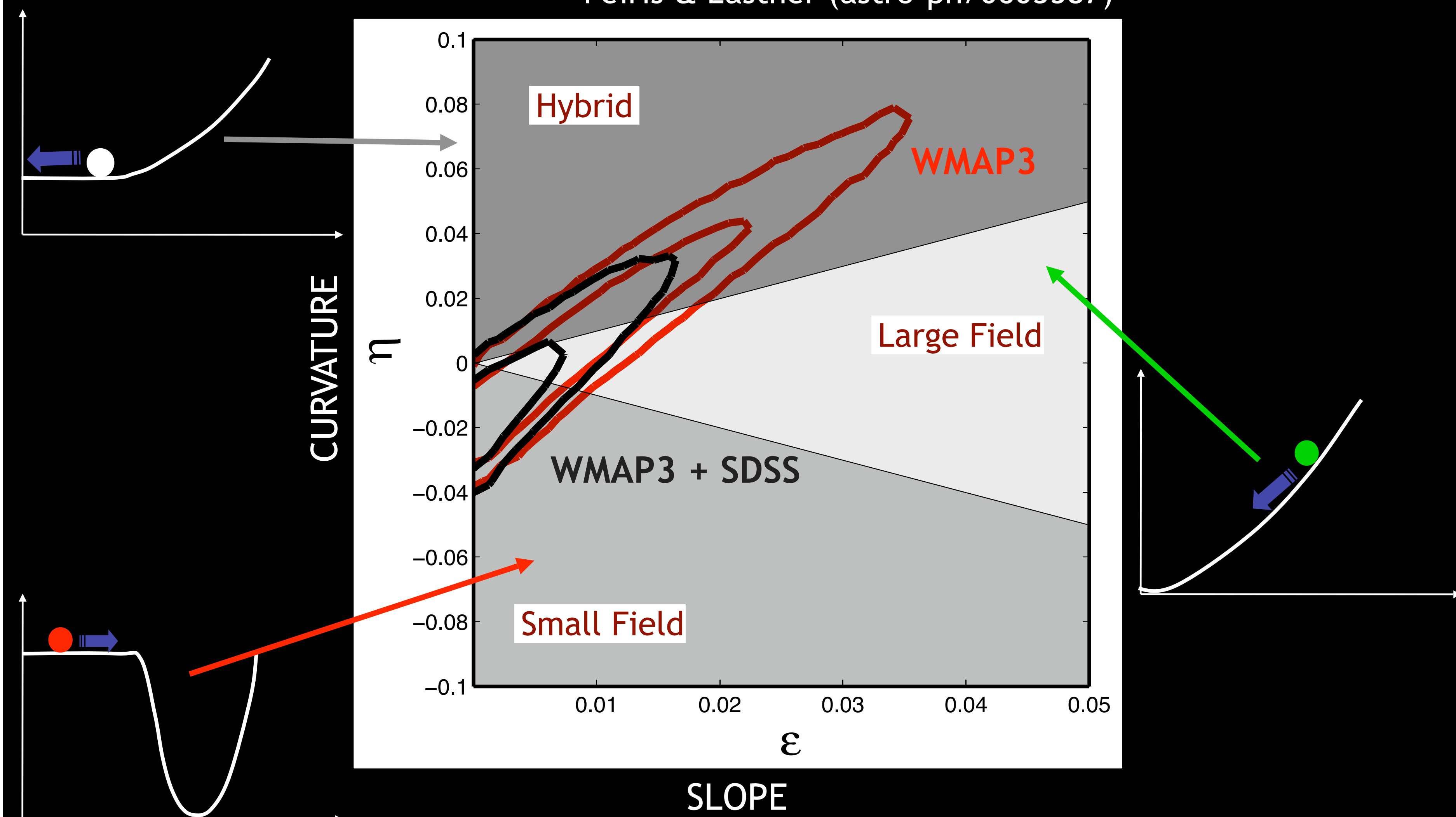
Fit to data: Slow Roll Reconstruction



Peiris & Easther (astro-ph/0603587), Peiris & Easther (astro-ph/0609003)

The Inflationary Zoo

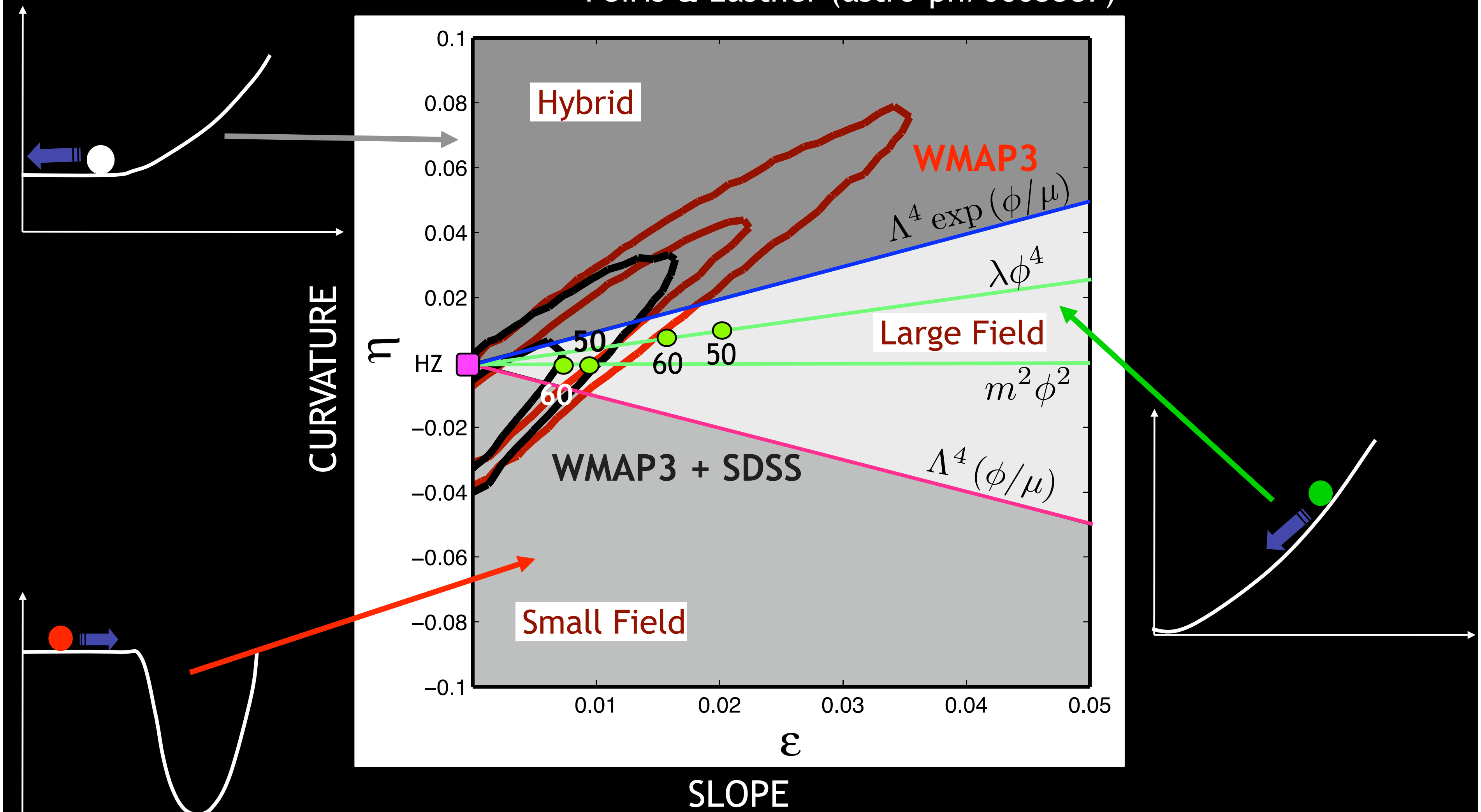
Peiris & Easther (astro-ph/0603587)



Constraints on first two Hubble Slow Roll parameters at k=0.002 Mpc^{-1}

Denizens of the Inflationary Zoo

Peiris & Easther (astro-ph/0603587)



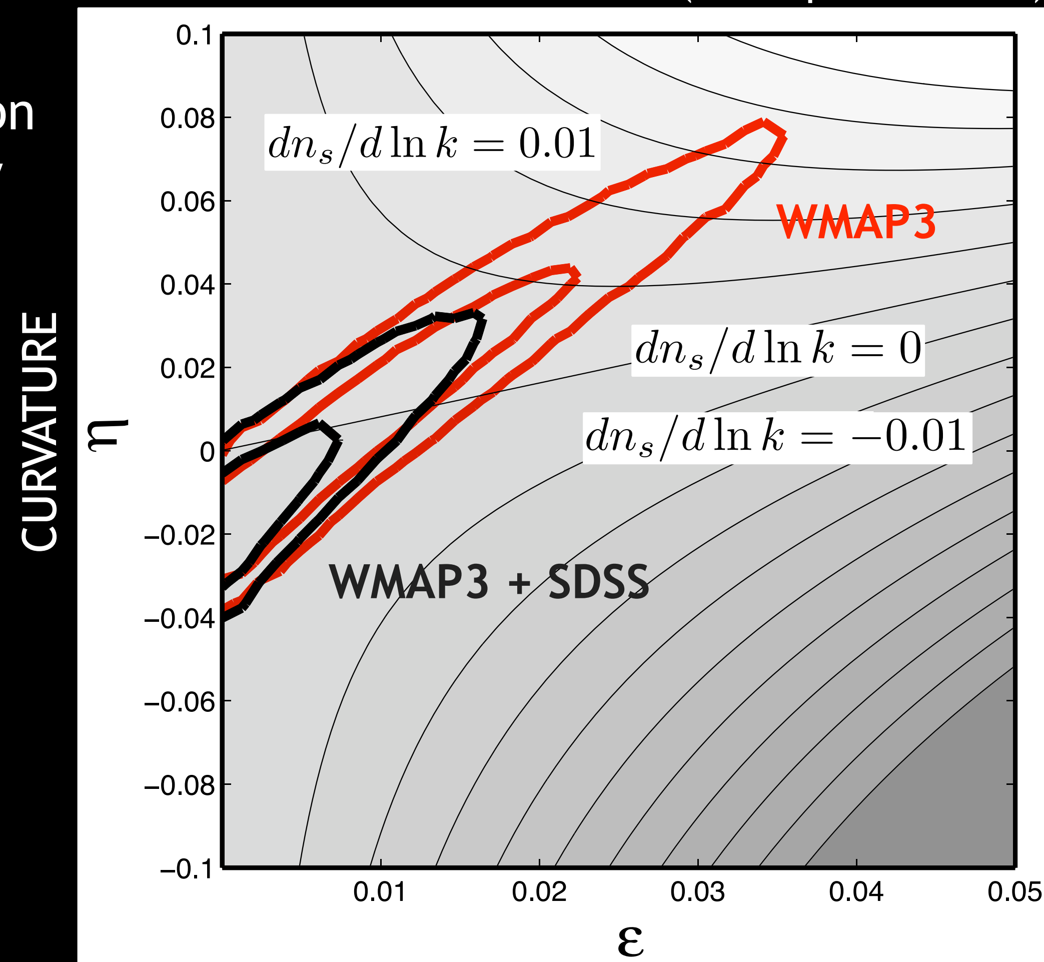
Constraints on first two Hubble Slow Roll parameters at k=0.002 Mpc^{-1}

What about the running of the spectral index?

- WMAP3 has tentative indication of "running" - n_s is potentially a function of k
- With only ε and η running is necessarily small
  - Running ~ ε^2 and εη
  - Add ξ to make running (potentially) large

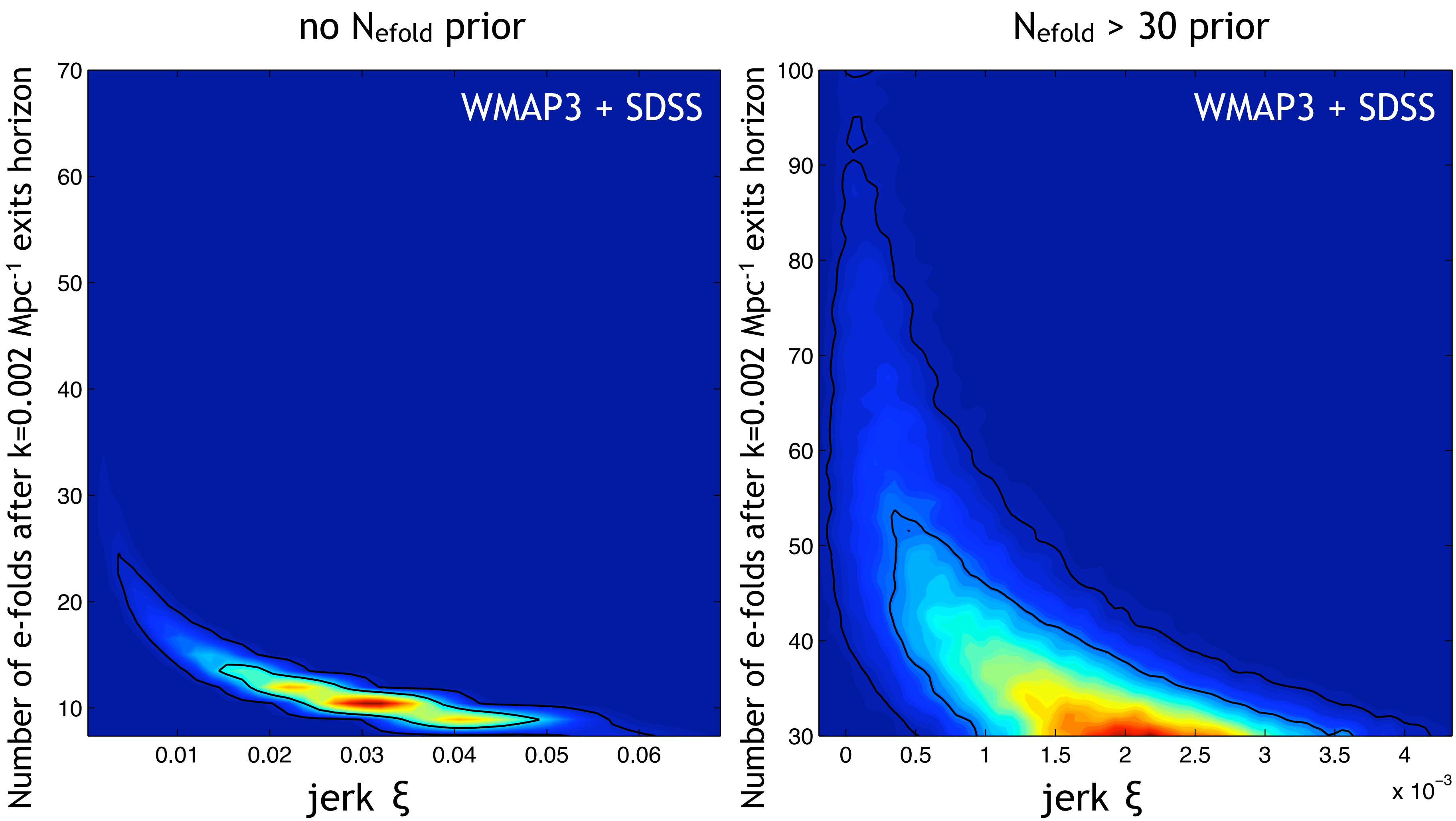
$$\alpha \simeq -2\xi + 16\epsilon\eta - 24\epsilon^2$$

Peiris & Easther (astro-ph/0603587)



SLOPE

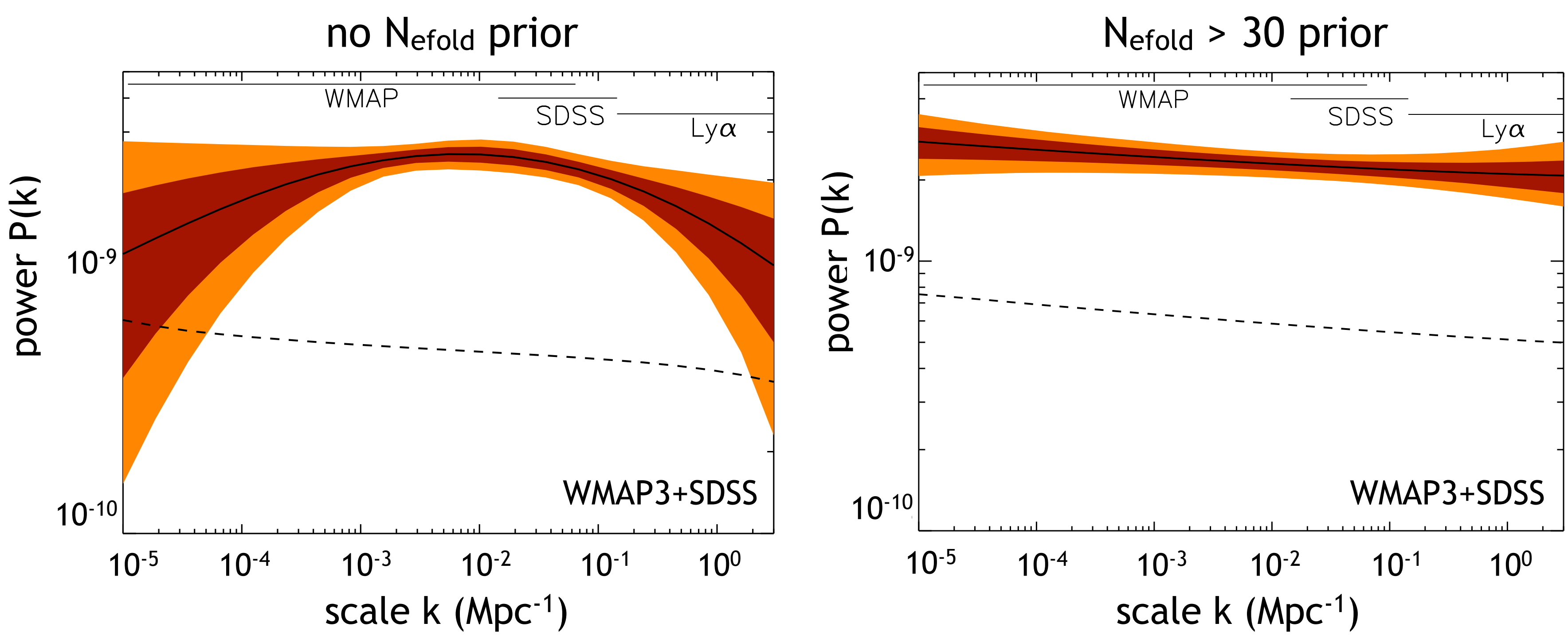
Constraints on the duration of inflation



$$N \simeq 60 + \frac{1}{6}\ln(-n_T) + \frac{1}{3}\ln(T_{RH}/10^{16}\mathrm{GeV}) - \frac{1}{3}\ln\gamma \qquad \alpha \simeq -2\xi + 16\epsilon\eta - 24\epsilon^2$$

Easther & Peiris (astro-ph/0604214), Peiris and Easther (astro-ph/0609003)

Reconstructed primordial power spectra

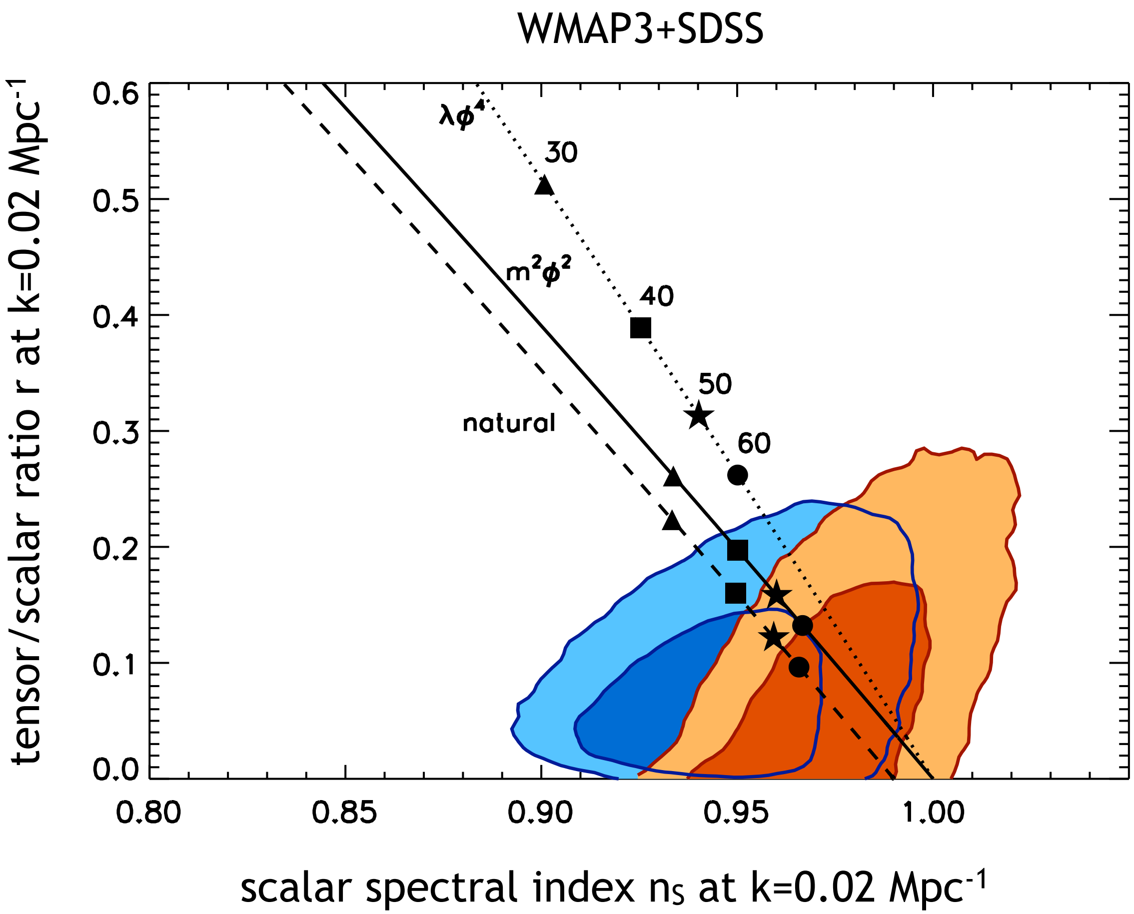


$$P_{\mathcal{R}} = \frac{[1-(2C+1)\epsilon + C\eta]^2}{\pi\epsilon}\left(\frac{H}{m_{\rm Pl}}\right)^2 |_{k=aH}$$

$$P_h = [1-(C+1)\epsilon]^2 \frac{16}{\pi}\left(\frac{H}{m_{\rm Pl}}\right)^2 |_{k=aH}$$

Peiris and Easther (astro-ph/0609003)

Bounds on spectral parameters at k=0.02 Mpc^{-1}

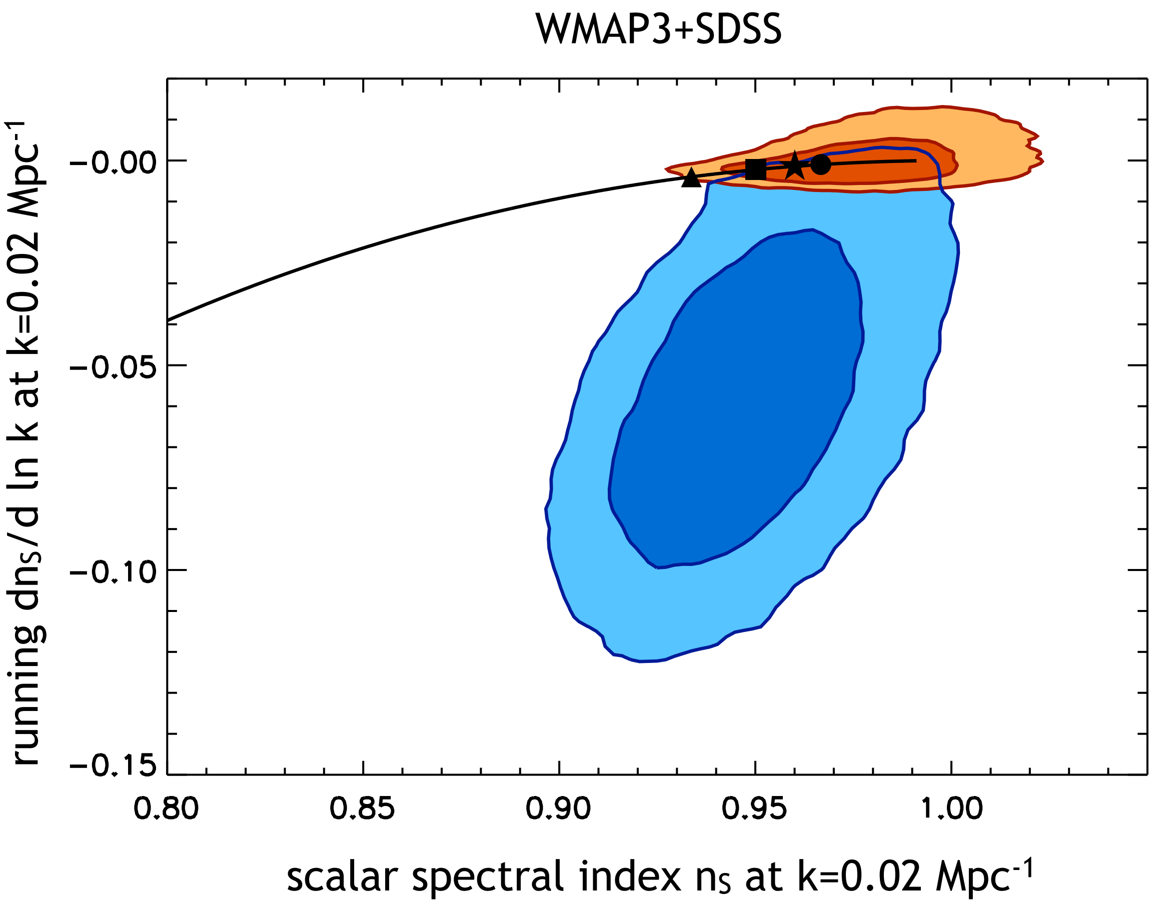


No N_{efold} prior

N_{efold} > 30 prior

Peiris and Easther (astro-ph/0609003)

Bounds on spectral parameters at k=0.02 Mpc^{-1}



No N_{efold} prior

N_{efold} > 30 prior

Peiris and Easther (astro-ph/0609003)

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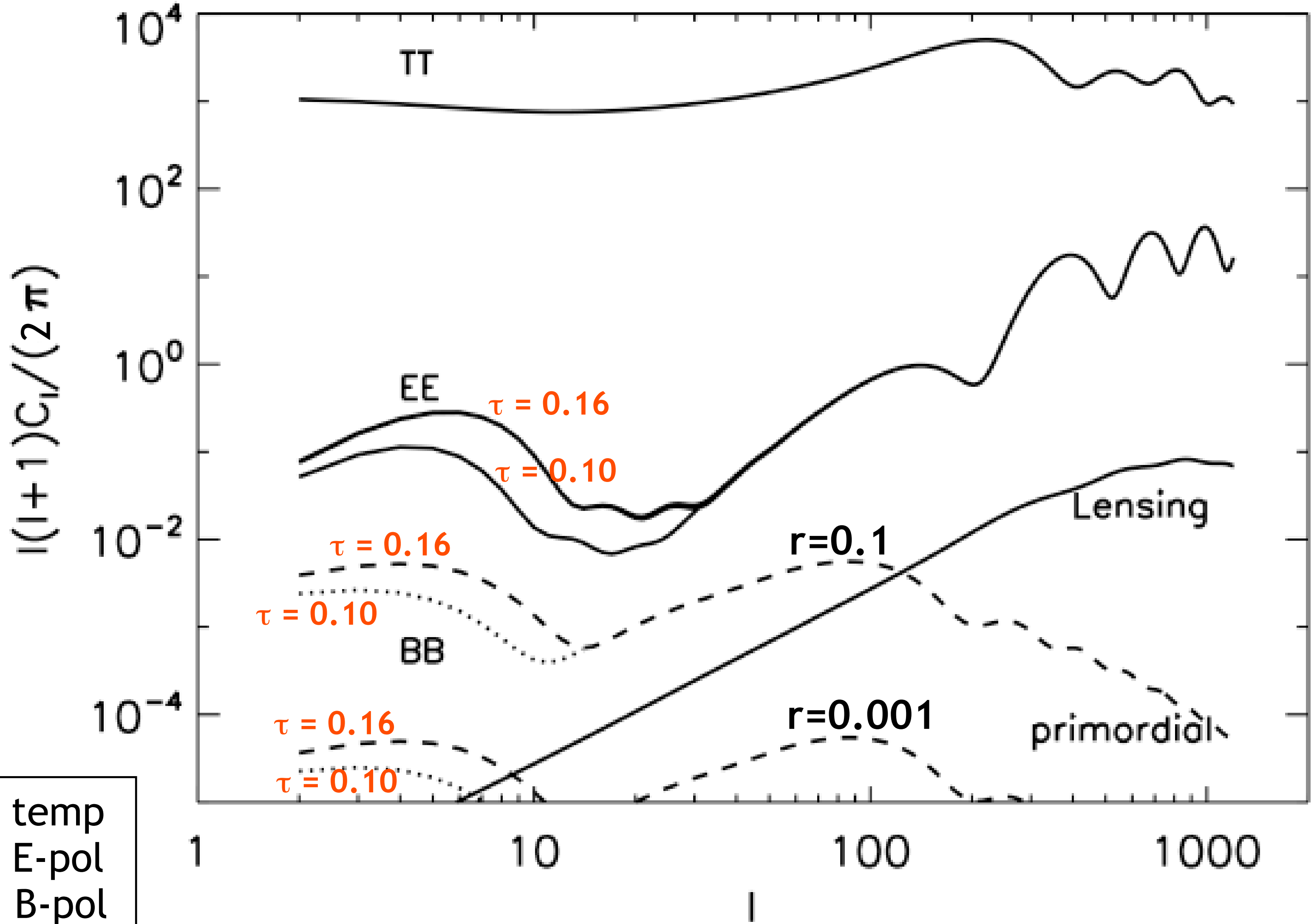
Future observational prospects

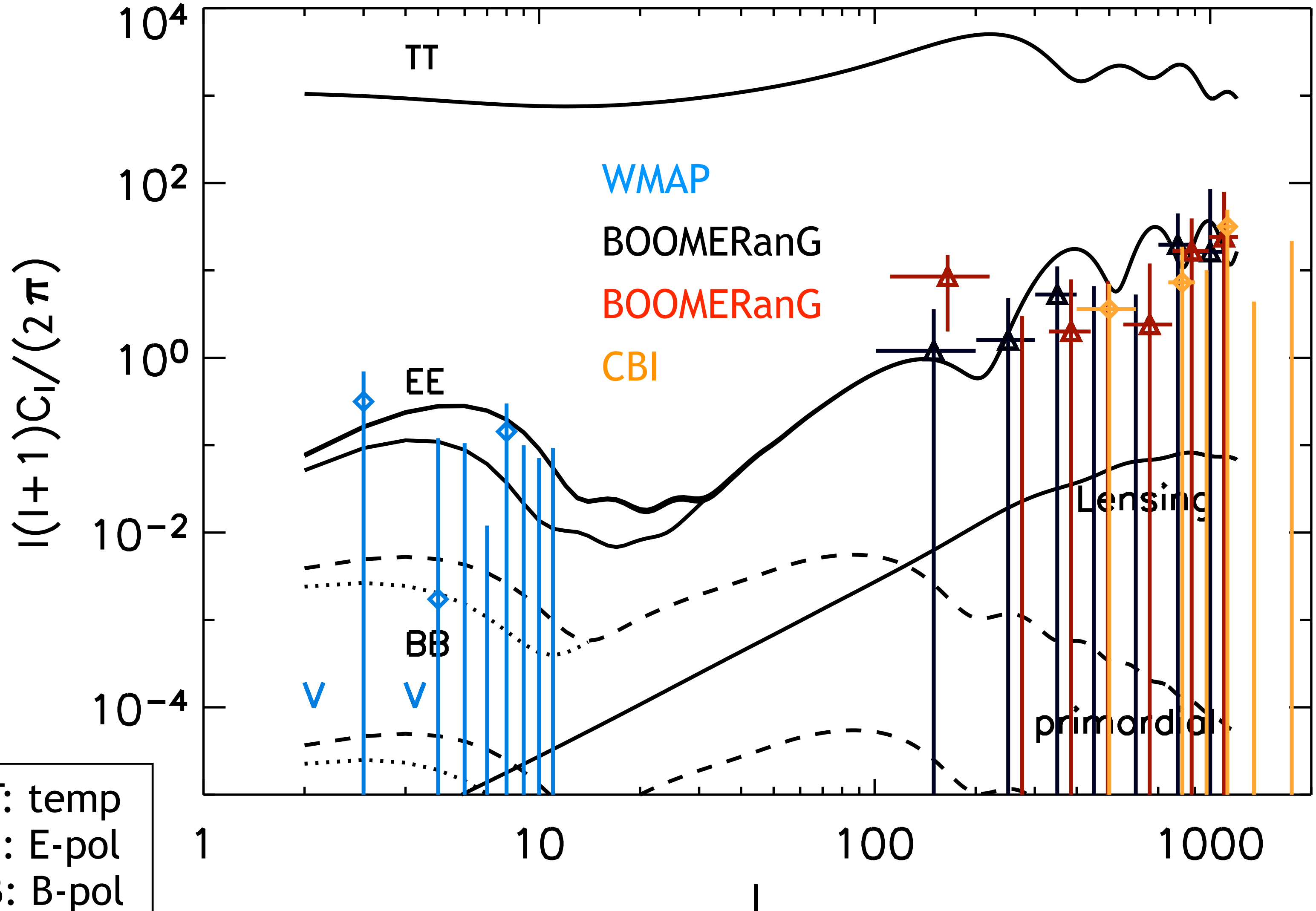
- Go to small scales! Much better measurements of the primordial power spectrum shape.
  - Planck l~3000 (k~0.2/Mpc)
  - ACT l~10000 (k~0.7/Mpc) [secondary effects]
  - Galaxies k~1/Mpc [non-linearity & bias]
  - Lyman alpha k~5/Mpc [gas phys. & radiation feedback]
  - Reionization k~50/Mpc [much is unknown]
- Detecting gravitational waves!
  - CMB: QUaD, BICEP, QUIET, CLOVER, PolarBear, EBEX, SPIDER, Planck, Inflation Probe etc… [large scales]
  - GWO: direct detection of primordial gravitational waves (BBO) [solar system scales]

Relative Amplitudes of CMB power spectra



TT: temp
EE: E-pol
BB: B-pol

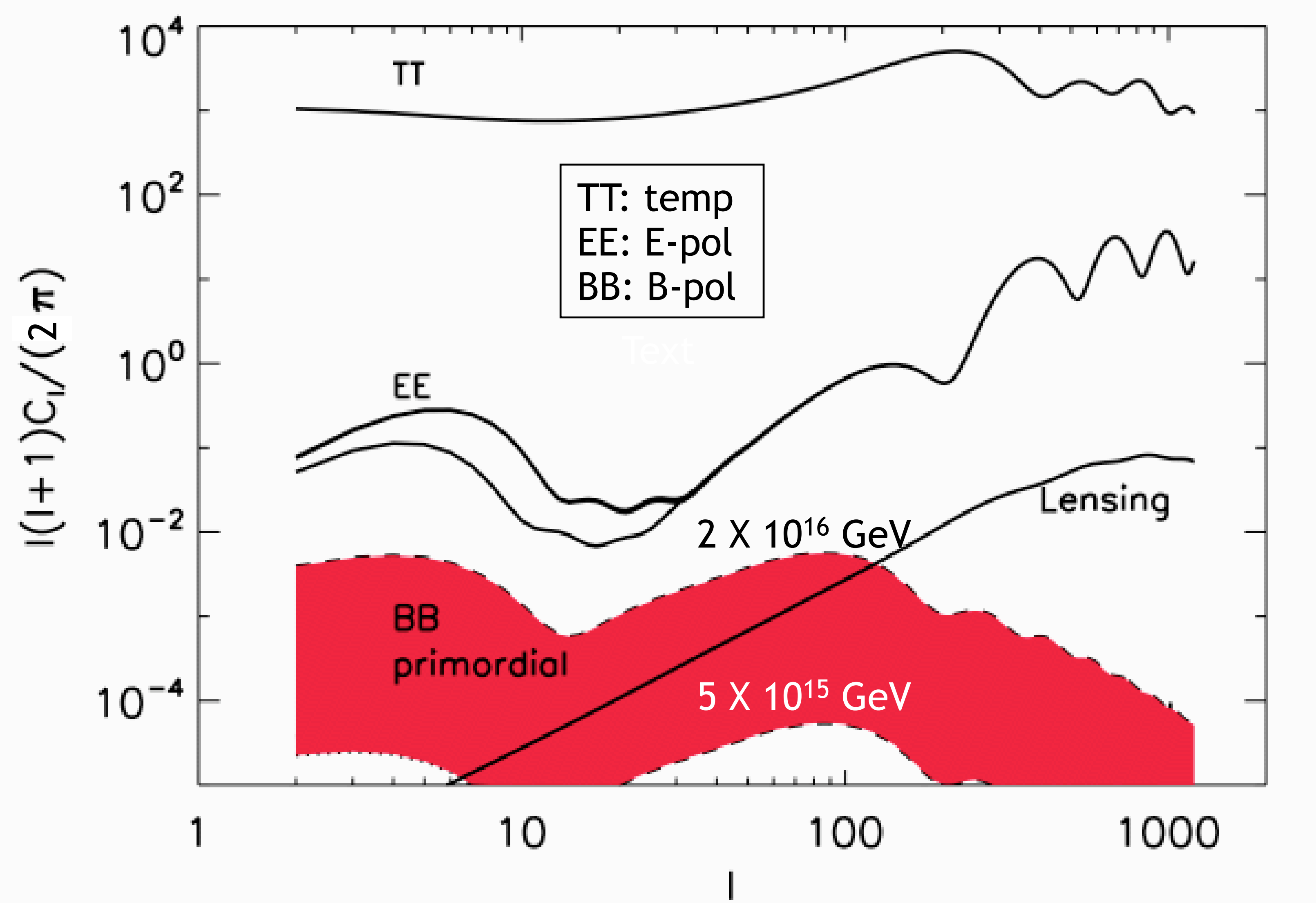
Current limits on B modes



TT: temp
EE: E-pol
BB: B-pol

Approximate range of primordial B-modes accessible to upcoming experiments

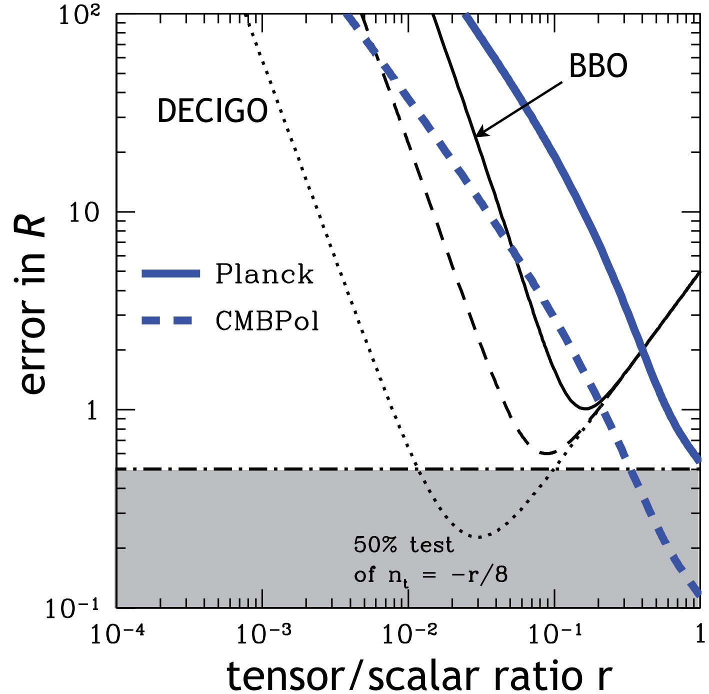
$$V^{1/4} \simeq 3.3 \times 10^{16} r^{1/4}\ \mathrm{GeV}$$



Testing the single field consistency relation

$$R = \frac{-r}{8n_t}$$

tensor spectral index



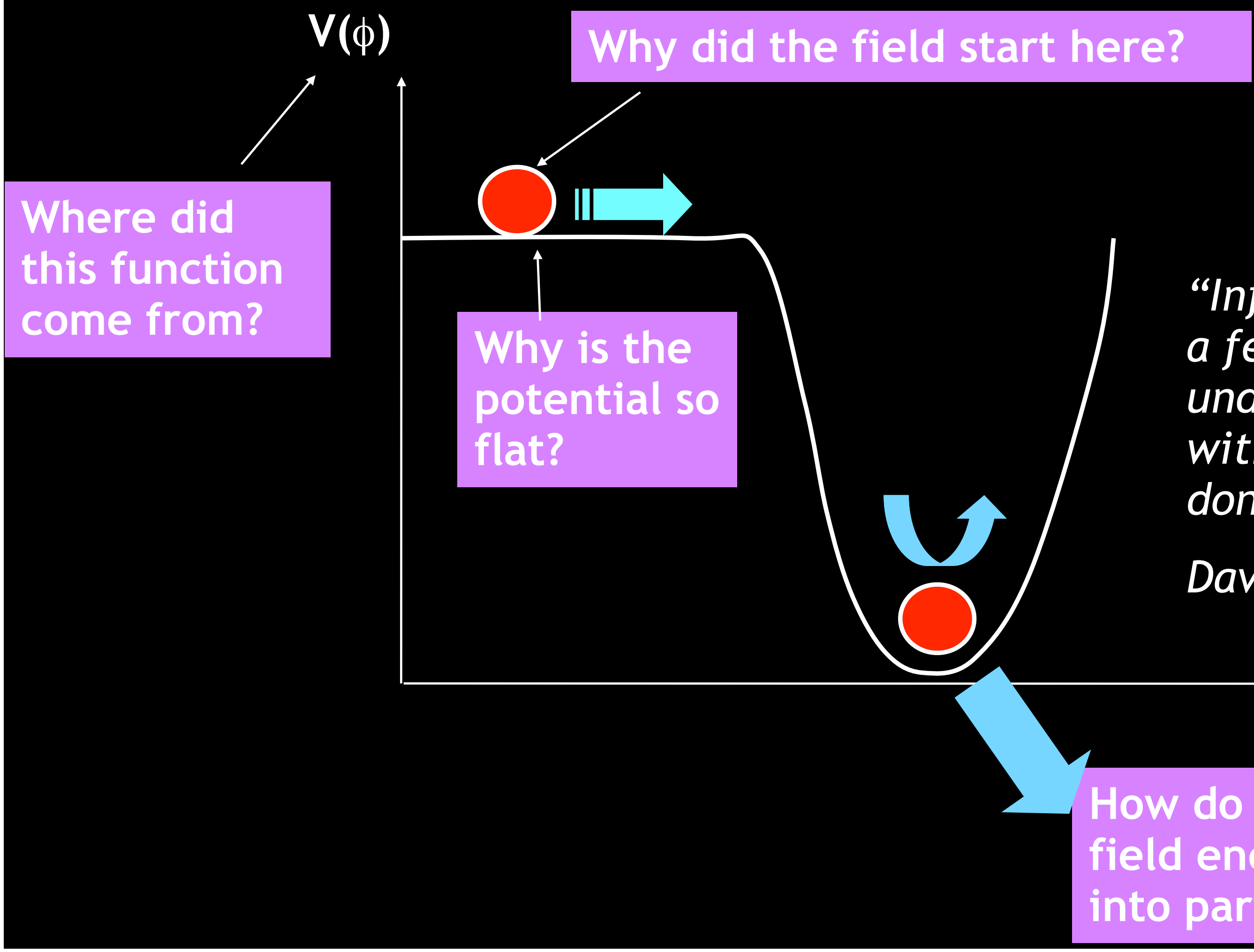
- *R*=1 if simplest form of inflation occurred: can we test its accuracy to R=1±0.5?
- Try combining measurements at CMB scales with direct detection measurements at 1 Hz (40 e-folds apart)
- Smoking gun of GUT scale physics

Seto (2005), Jimenez, Verde and Peiris (2005), Smith, Peiris, & Cooray (2005)

Future observational prospects

- Go to small scales! Much better measurements of the primordial power spectrum shape.
  - Planck l~3000 (k~0.2/Mpc)
  - ACT l~10000 (k~0.7/Mpc) [secondary effects]
  - Galaxies k~1/Mpc [non-linearity & bias]
  - Lyman alpha k~5/Mpc [gas phys. & radiation feedback]
  - Reionization k~50/Mpc [much is unknown]
- Detecting gravitational waves!
  - CMB: QUaD, BICEP, QUIET, CLOVER, PolarBear, EBEX, SPIDER, Planck, Inflation Probe etc… [large scales]
  - GWO: direct detection of primordial gravitational waves (BBO) [solar system scales]
- Detecting non-Gaussianity from 2nd order gravity?
  - Can we detect f_{NL}~1?

Inflation: Theoretical Front



"Inflation consists of taking a few numbers that we don't understand and replacing it with a function that we don't understand"

David Schramm 1945 -1997

Dirac-Born-Infeld (DBI) Inflation

- warped flux compactification of type IIB string theory to 4 dimensions

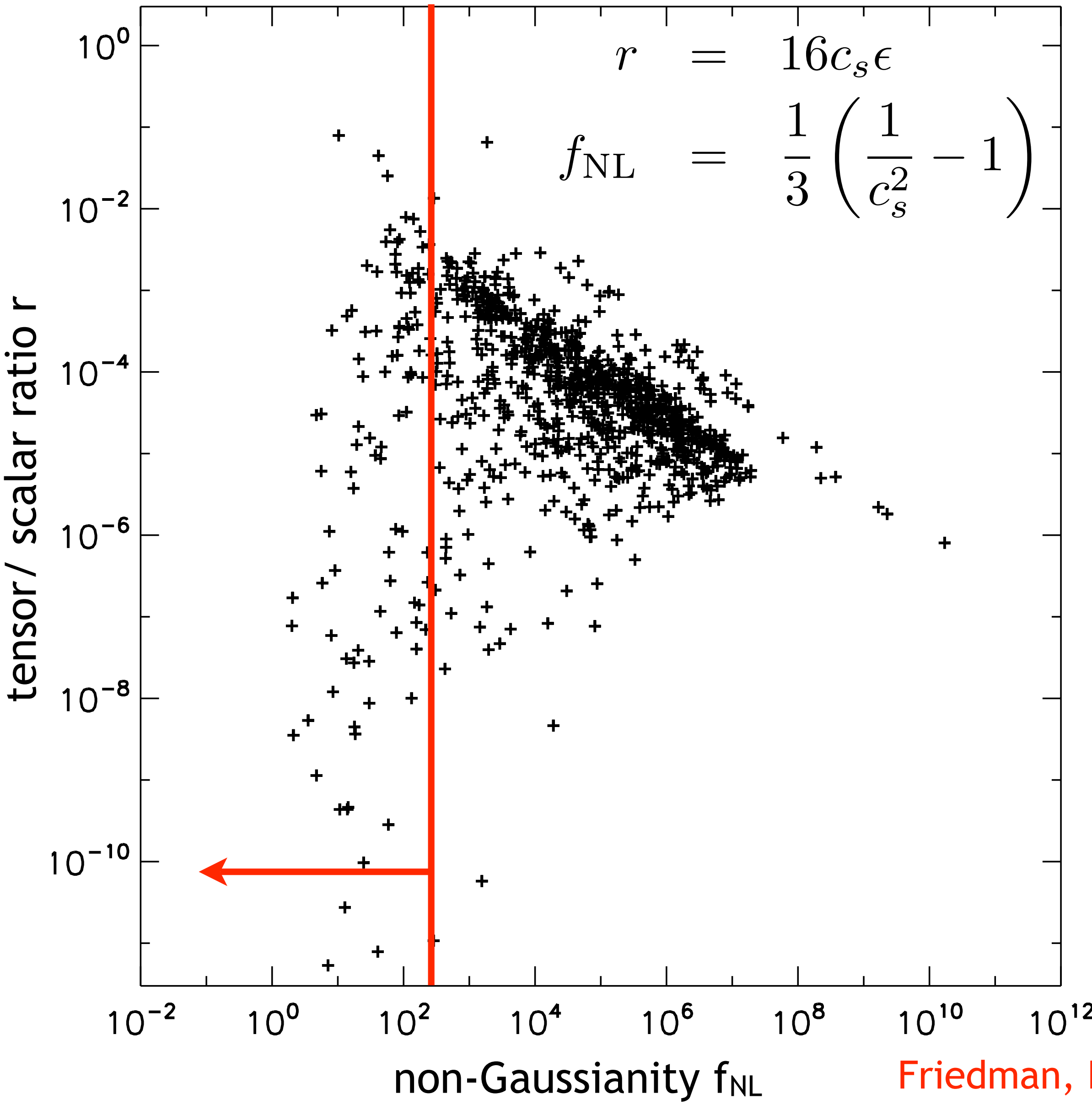
- internal space has a conical (warped) throat in which inflation takes place as a D3-brane falls in and annihilates with an anti-D3 brane in the throat

- kinetic term of inflaton (open string mode) appears in DBI action

- even when potential is steep, DBI action leads to Lorentz factor: the limiting speed of the scalar field is small even when it's becoming ultra-relativistic (sufficient inflation obtained)

e.g Silverstein and Tong (2004), Alisahiha et al. (2004)

Simulated DBI Inflation with general sound speed



Friedman, Baumann, Peiris & Cooray (in prep)

Inflation: Future Work

- Look at all sources of information
  - CMB: WMAP-N, ACT, Planck, B-Pol
  - Large scale structure (SDSS, LSST, ...)
  - Ly-α forest
  - High z 21 centimeter
  - Direct detection of primordial GWs (BBO)

Large scale

Solar system scales

- Constrain inflationary dynamics and reheating physics

- Can we put data constraints on stringy physics?!

Roadmap

- Background: cosmic acceleration
  - Inflation
  - Dark energy

- Constraining Inflation with Cosmological Data
  - "Worked example": Cosmic Microwave Background
  - WMAP data and "standard" inflationary constraints
  - Slow Roll Reconstruction: connecting theory and data
  - Future Prospects

- Constraining Dark Energy with Cosmological Data
  - Extending reconstruction toolbox to dark energy
  - Dynamics of generic quintessence potentials
  - Future Prospects

Inflation vs Dark Energy

Inflation	Dark Energy
> 10^{15} GeV (theoretical)	10^{-3} eV (observed)
H ~ constant	H can have large slope (effect of matter and radiation)
V ~ const	V slope can be large too (DE not necessarily potential dominated)
inflation has to last ~60 e-folds so potential described by a slow roll expansion	observables probe a couple of e-folds - cannot justify a slow roll expansion (no small parameters)
observables are perturbation spectra	directly probe the expansion history (perturbations very difficult to observe)

Ingredients of Model

Equation of Motion

$$\ddot{\phi} + 3H\dot{\phi} + \frac{dV}{d\phi} = 0$$

$+$

Friedmann Equation

$$H^2 = \frac{8\pi G}{3}\rho$$

Potential Generator $V(\phi)$

$$\epsilon \propto \left(\frac{V'}{V}\right)^2 \qquad \eta \propto \frac{V''}{V} \qquad \xi \propto \frac{V'''V'}{V^2}$$

$+$

Initial Conditions

$$\Omega_{\rm DE}^{\rm start} \in [0, 1]$$
$$w^{\rm start} \in [-1, 1]$$
proxy for field velocity
$$\epsilon^{\rm start} \in [0, \infty]$$
$$\eta^{\rm start} \in [-\infty, \infty] \quad \text{etc}$$

Huterer & Peiris (astro-ph/0610427)

Data Compilation

Probe background expansion using a combination of standard candles, standard rulers, and measurements of the present expansion rate, accounting for STATISTICAL and SYSTEMATIC errors.

- Current data
  - SNLS Supernovae (~115), includes low-z
  - WMAP [standard ruler, baryon/dark matter densities]
  - Baryon Acoustic Oscillations (BAO) [SDSS, distance to z=0.35]
  - H_0 to 10% [Hubble Key Project]
- Future data - centered on LCDM
  - SNAP Supernovae (~2800) with systematics
  - Planck [standard ruler, baryon/dark matter densities]
  - BAO [10,000 sq. deg, 0.5<z<2.0]
  - H_0 to 5%

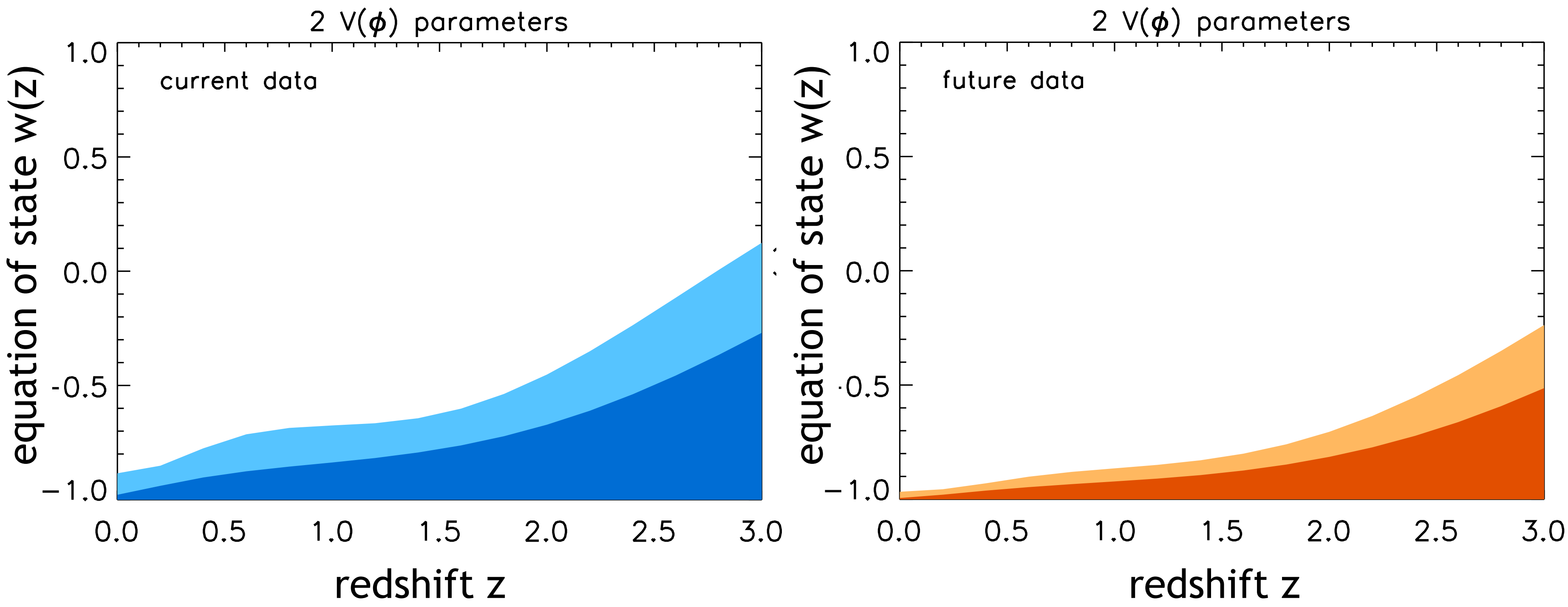
Huterer & Peiris (astro-ph/0610427)

Reconstruction of the equation of state

$$w(z) = \frac{\dot{\phi}^2/2 - V(\phi)}{\dot{\phi}^2/2 + V(\phi)}$$

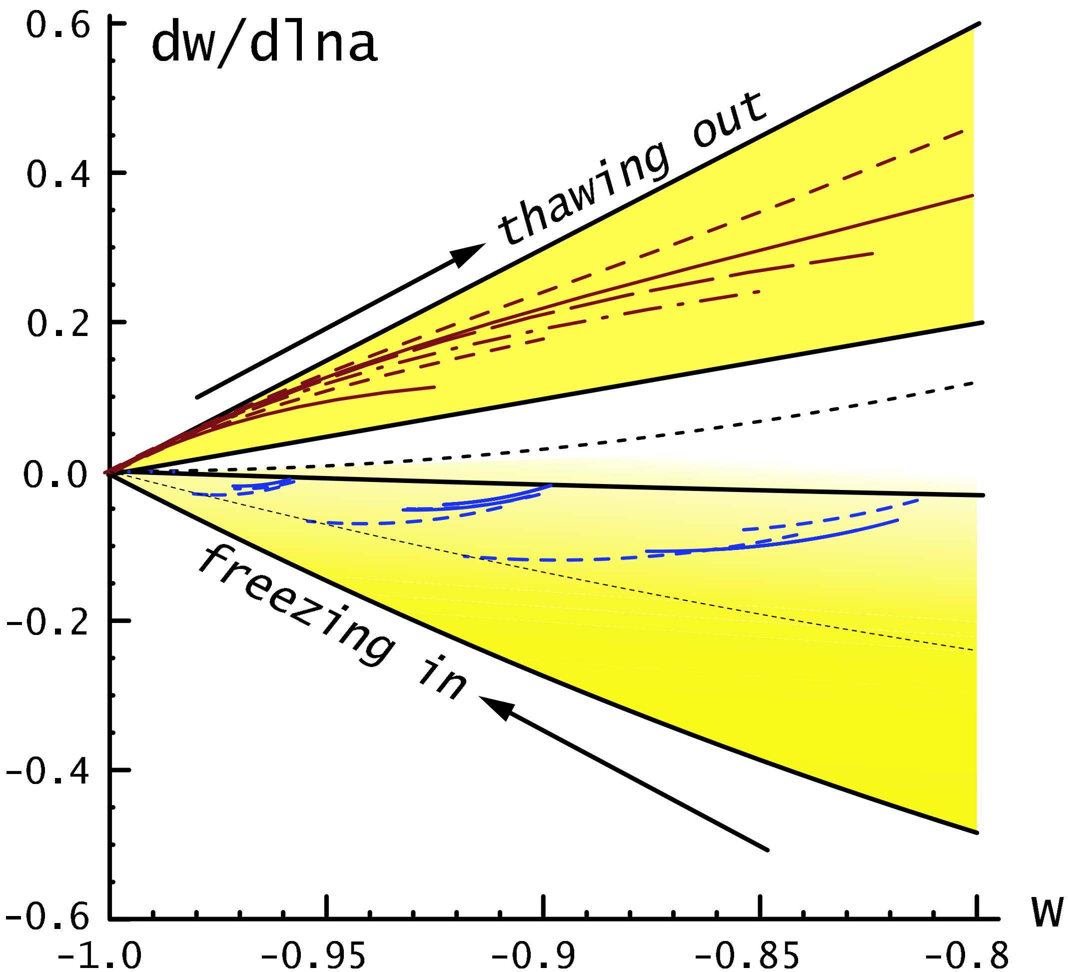
pressure

density



Huterer & Peiris (astro-ph/0610427)

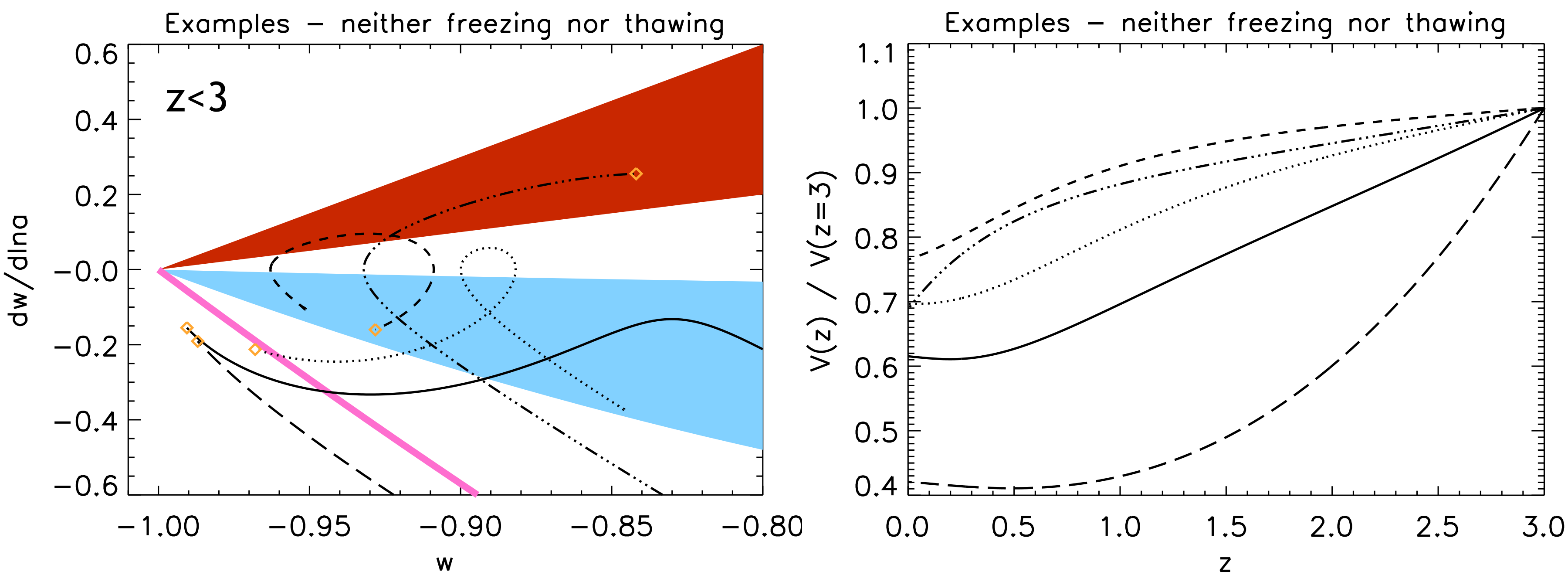
Generic behavior of scalar field models?



Q: Do dark energy models with general potentials obey a "freezing/thawing" classification?

Caldwell and Linder (2005)

Thawing and freezing?

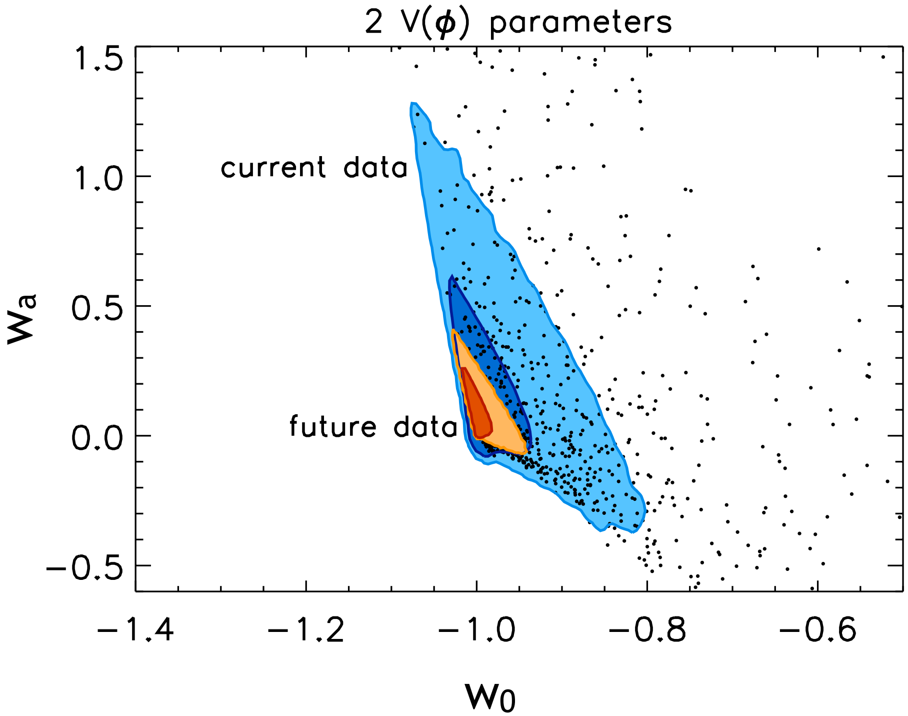


THAWING OUT

FREEZING IN

Huterer & Peiris (astro-ph/0610427)

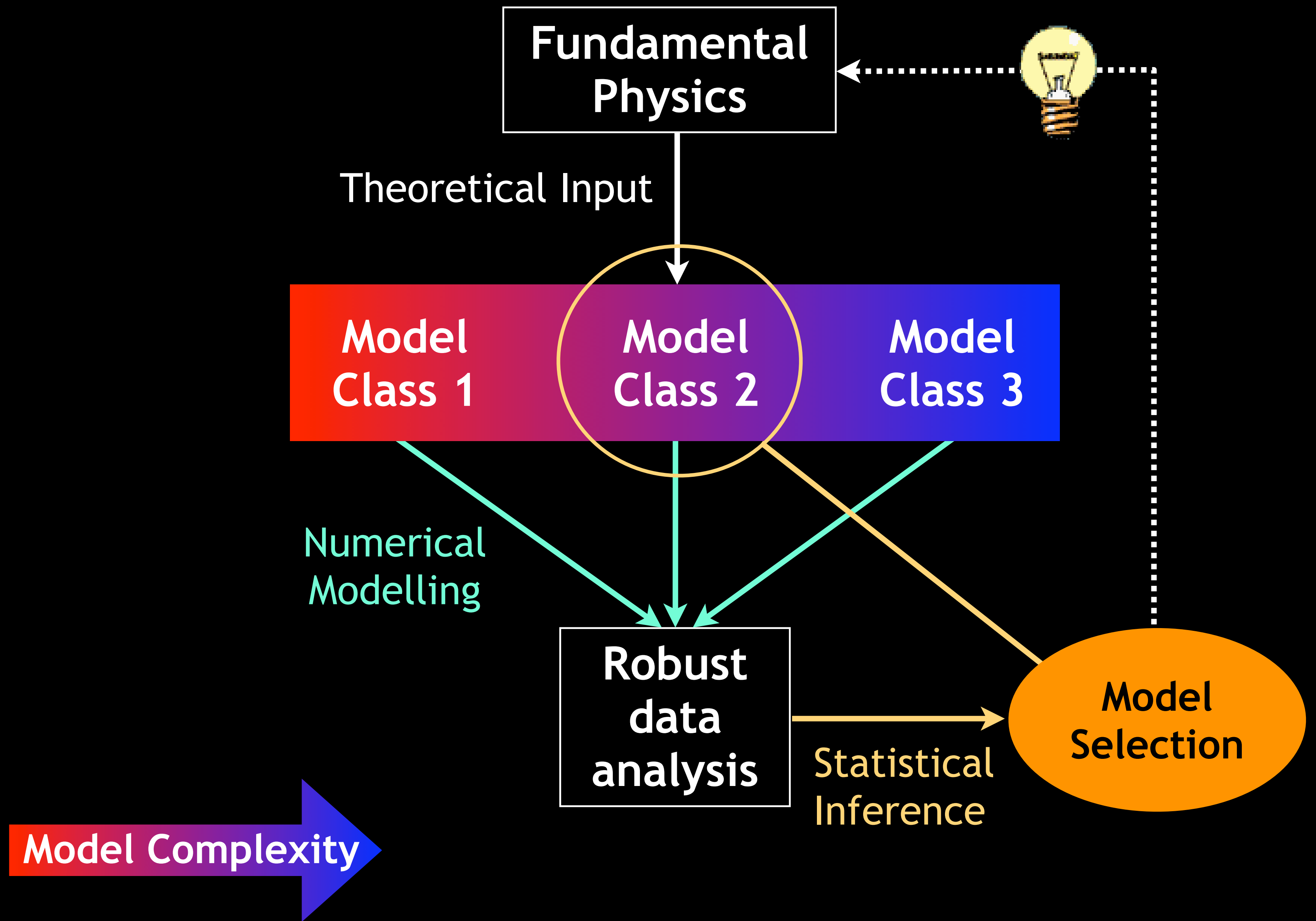
Dark Energy: Future Work

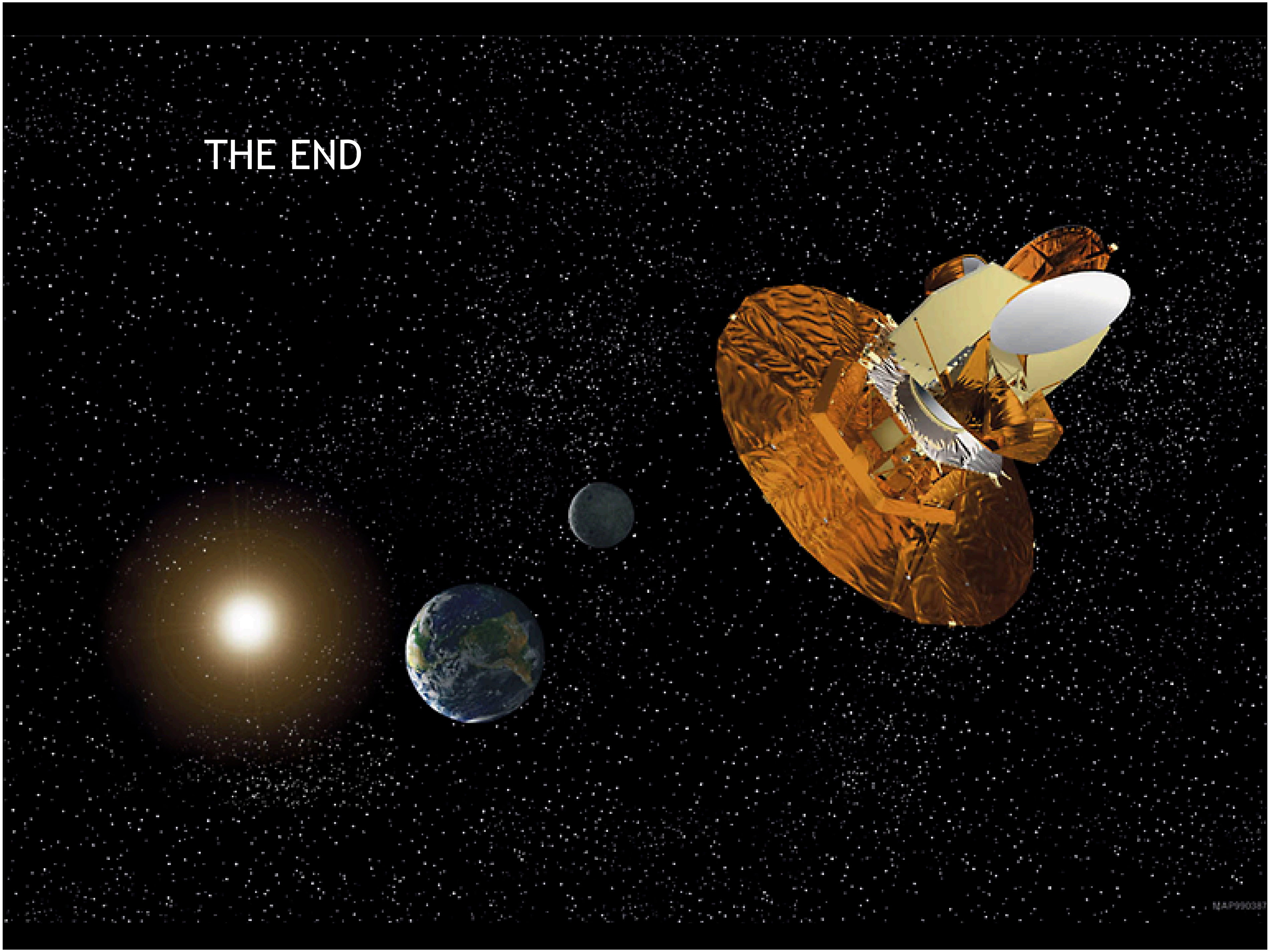


$$w(z) = w_0 + w_a \frac{z}{1+z}$$

- "Figure of merit" improvement current/future = 10
- Only used background evolution so far - add probes of the growth of structure
- Investigate clustering of dark energy
- Investigate coupling of dark energy to dark matter

Summary of Research Methodology

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